Electric Generators

OPERATION AND MAINTENANCE

BOOKS IN THE ELECTRICAL SERIES

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)PERATION AND MAINTENANCE

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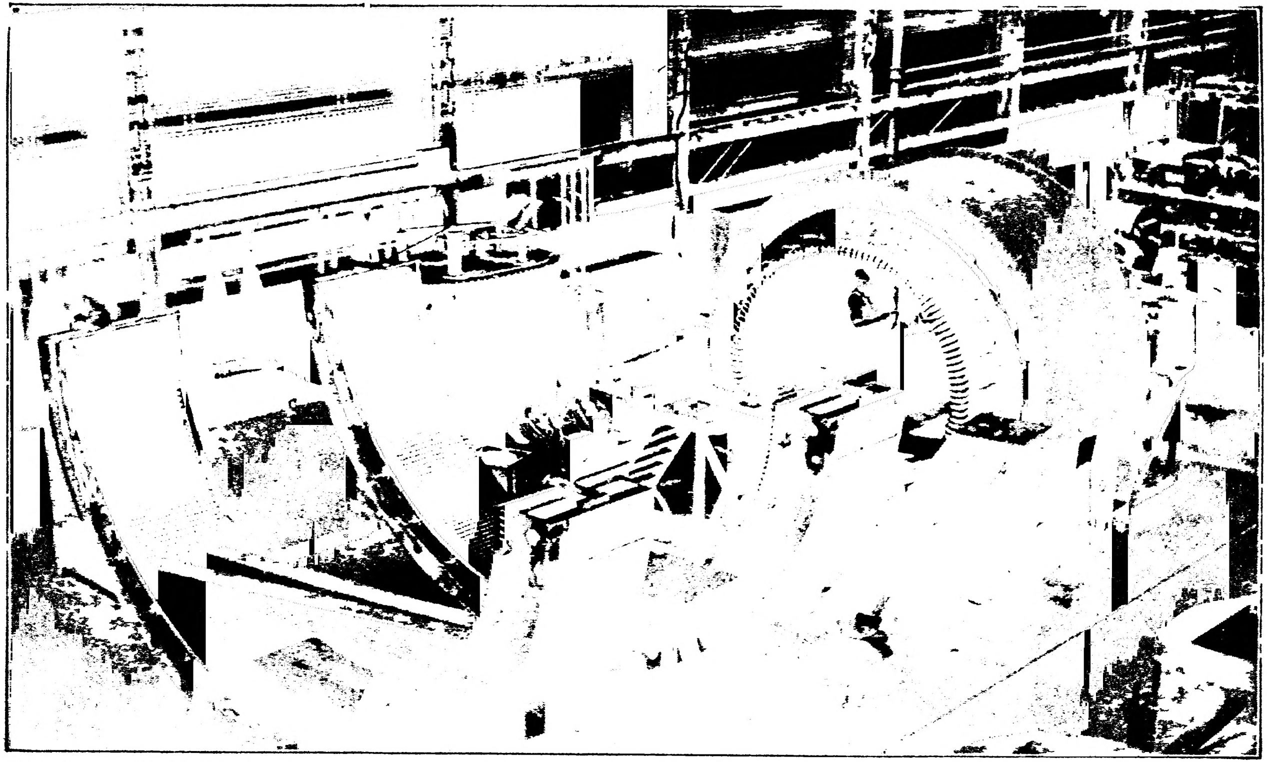
Parallel operation of generators is treated in a practical manner, starting with a brief explanation of fundamental principles, and proceeding to methods of synchronizing, checking phase sequence, adjustment of field current, etc.

A hydroelectric plant is usually tied in to a large power system that may extend many miles away from the power plant. Satisfactory operation of this large power system depends on the proper operation and maintenance of the electrical equipment in the hydroelectric plant.

To assist the man working in the plant, many of the common troubles that occur are listed along with the probable cause and the proper remedy to apply. This material is arranged in the form of tables to provide a quick reference. These tables include the care of alternators, exciters, voltage regulators, power transformers, relays, and lightning arresters. A careful reading and study of these troubles will prepare the operating and maintenance man for an emergency and will enable him to decide quickly what to do and how to do it. In this way, valuable time will not be lost in restoring service.

THE AUTHORS

The text material in this volume also appears in Applied Electricity Cyclopedia.



THE TWO GIANT SEMI-CIRCLES ARE THE STATOR FOR A WATER WHEEL GENERATOR IN WHICH ARMATURE COILS WILL BE PLACED

In the background is the stator of a 60,000 kva synchronous condenser

CONTENTS

*For page numbers, see foot of pages.

SYNCHRONOUS MOTOR-GENERATOR SETS OF 5000 KILOWATT CAPACITY

The 13,200-volt synchronous motor in the center drives two 2500 KW 750-volt D.C. generators and two 250-volt exciters.

Courtesy of Allis-Chalmers Manufacturing Company

TYPES OF ALTERNATING-CURRENT GENERATORS

The only difference between a simple direct-current generator and a simple alternating-current generator is that the direct-current generator has a commutator and the alternating-current generator has slip rings. From this slight difference in construction comes the difference in the voltage and kind of current obtained from the two units.

FREQUENCY OF ALTERNATING CURRENT

Frequency of an alternating current is the number of cycles the current passes through in one second. A complete turn of a loop of wire will make one complete voltage cycle as shown in Fig. 1. One-

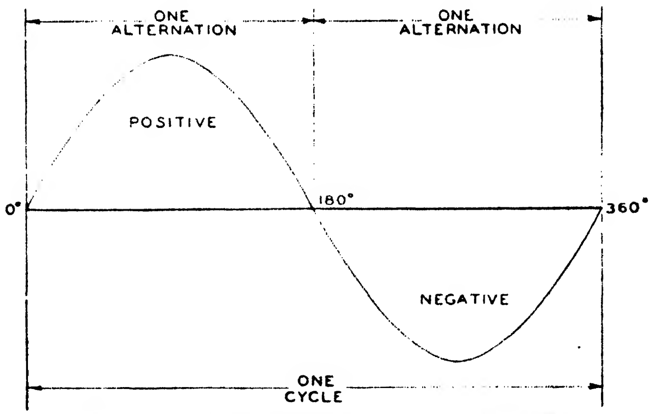


Fig. 1. Curve of Voltage Obtained from Revolving a Loop of Wire between a Pair of Poles

half the rotation of the loop will produce a voltage in a positive direction which causes current to flow out on the outside slip ring, and the next half turn completing the revolution will cause the outside ring to be negative. This shows that the current flows equally in both directions during a cycle. A reversal of current is called an alternation. Two alternations make one complete cycle.

Speed and Number of Poles. If this coil had rotated by two pairs of poles, the effect would have been just the same, as a coil making two complete turns with one pair of poles. Each time a coil or group of coils together pass a pair of poles a cycle is made. Obviously the speed and the number of poles will affect the frequency. Mathematically, frequency equals the poles times the revolutions per second divided by two and is often expressed as follows:

$$\text{Frequency} = \frac{\text{r.p.m.} \times \text{p}}{60 \times 2}$$

If the pole pieces were rotated and the coils remained stationary, the frequency would be exactly the same as it is with the revolving

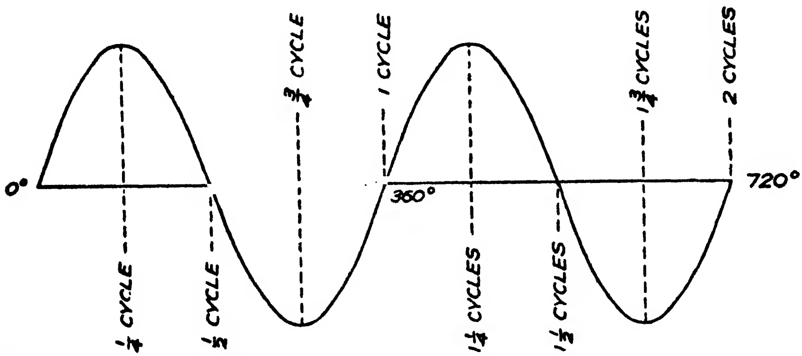


Fig. 2. Curve Showing Variation of Voltage When Loop Makes Two Complete Turns or Two Pairs of Poles Are Used

loop. A pair of poles passing a coil produce two alternations or one cycle, and the coil passes through 360 electrical degrees. If this had been a 4-pole machine, two complete cycles, Fig. 2, would have occurred on the coil or 720 electrical degrees. Each pair of poles adds a cycle to the loop for each revolution that either the coil or the poles make.

Some small alternating-current generators use the revolving armature like a direct-current generator, but for two very important reasons the larger machines without exception use the revolving field in which the poles rotate. One important reason revolving fields are used is due to the fact that insulation stands up better if it is stationary, and the other is no sliding contacts for the large

currents are necessary with revolving fields. Moving parts are also lighter with the latter arrangement. Fig. 3 shows the various positions of the revolving loop with corresponding voltage produced in Fig. 2 for each quarter cycle. No voltage is produced at the first and third positions of the coil as the conductors are not cutting the flux in these positions as shown by Fig. 2. As the coil leaves the starting position, as shown in Fig. 3, the voltage gradually increases

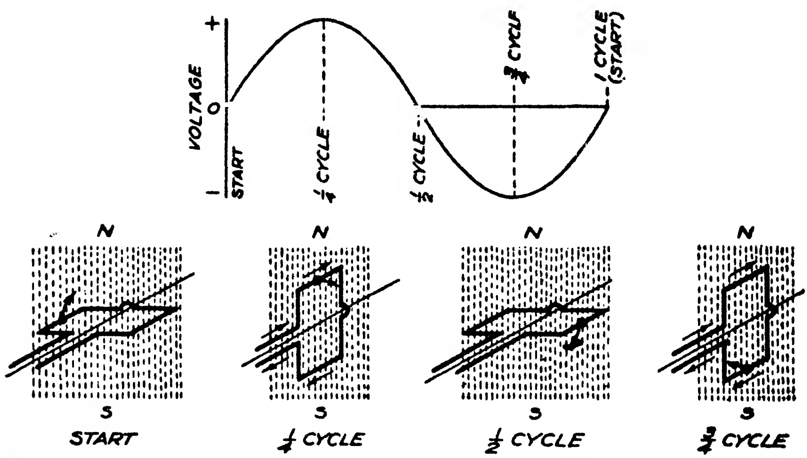


Fig. 3. Loop Positions and Instantaneous Voltages Shown as a Single Loop of Wire Is Revolved in a Magnetic Field

and the second picture shows the voltage at the highest point when the quarter cycle position is reached.

SINE CURVE

The sine curve shown in Fig. 1 is the standard of reference for all discussion on alternating current. This curve can be plotted graphically by using a sine table and the corresponding angles. The sine itself is simply the ratio of two sides of a right-angled triangle, being the altitude divided by the hypotenuse. The cosine referred to in power factor discussions is the ratio of the base to the hypotenuse. Each angle always has the same sine value, likewise a cosine value which is always the same number for any particular angle. A curve plotted from the sine values would always have a maximum value of one.

The sine curve, shown in Fig. 4, can be developed mechanically

from a circle as follows: Starting with a point *A* at position *O* make a circle about a center *C*. Draw a horizontal line to the right of the circle from *O* to *B* and divide it into sixteen equal lengths. (For more accurate work, more divisions should be used.) This line represents the time it takes point *A* to go around the circle and is measured in degrees 0 to 360. Divide the circumference of the circle into the same number of divisions as there are in the horizontal line. A vertical line from each one of these division points on the circumference to the horizontal line through *C* represents the value of voltage generated at this particular instant by the coil in passing through the pole flux. These lengths laid off vertically on the horizontal line will give points through which the sine curve can be drawn, as shown in Fig. 4.

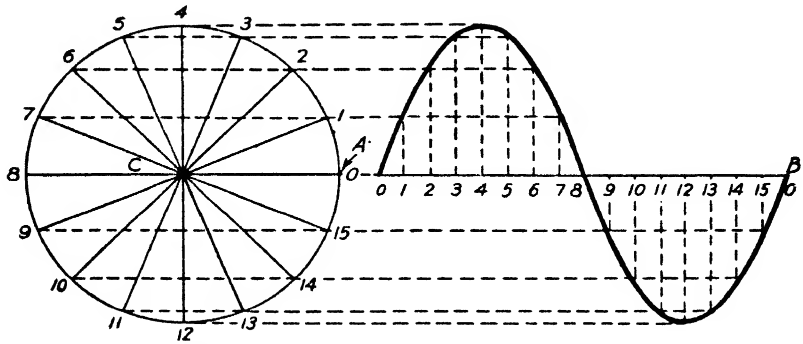


Fig. 4. Development of a Sine Curve from a Circle

The voltage curves for generators do not conform to the sine wave usually pictured, but take shapes similar to those shown in Fig. 5. These shapes give better operating results and are used with practically all commercial machines. The shape of this voltage wave can be changed to any desired form by changing the contour of the pole face. In this figure the pole face is flat and the air gap uniform, which produces the wave form shown. If the pole face was changed slightly so as to weaken the flux density at the front and rear sides of the pole, the wave form would be more peaked and would look more like the sine wave. The wave form shown in Fig. 5 is made by a single coil in the armature slot. Commercial generators ordinarily have more than one coil per slot so the wave form is not quite so flat topped but is more like the sine curve.

PHASE

The term phase, as used in electrical work and in literature, has two separate and distinct meanings. Unless these are clearly and definitely understood a great deal of confusion may result. One

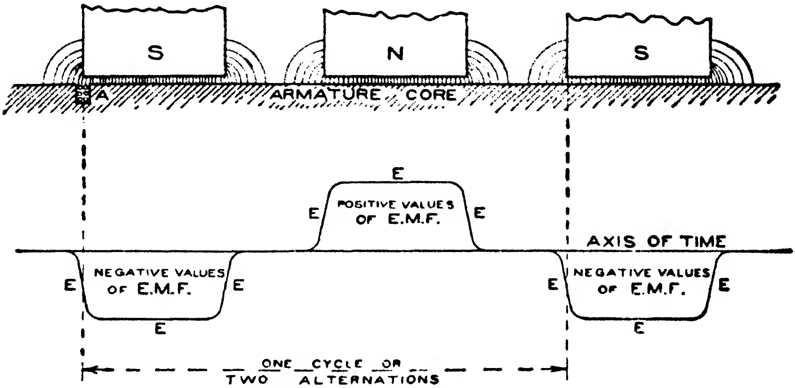


Fig. 5. Development of Magnetic Fields and Voltage Curve Obtained from Them

meaning of the term phase has to do with circuits. Single-phase, two-phase, three-phase, and six-phase circuits are frequently mentioned in discussing alternating-current circuits.

A single-phase circuit may be defined as one which has voltage

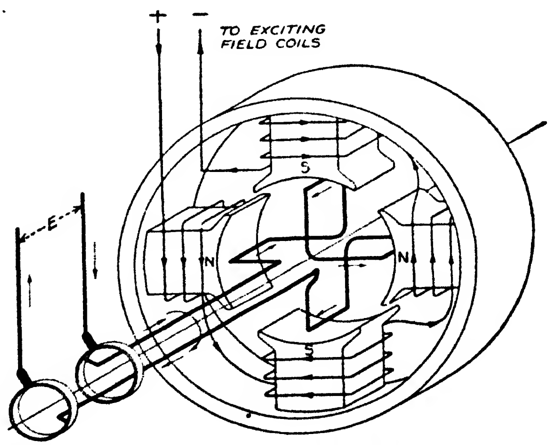


Fig. 6. A Single-Phase Alternator with a 4-Pole Revolving Armature. Phases are determined by windings and not by the number of poles

impressed upon it from only one alternating-current source. A single wire or coil revolving in a magnetic field will produce a single-phase circuit. The revolving coil shown in Fig. 3 would be a single-phase generator. The number of turns or the number of loops would

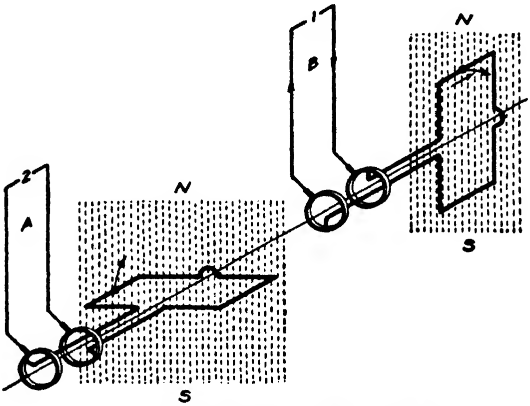


Fig. 7. Elementary Two-Phase Generator

not change the phases which are also independent of the number of poles as shown in Fig. 6. Although this machine has four poles and two loops, it is only a single-phase generator, as there is only one voltage wave acting on any circuit connected to the slip rings.

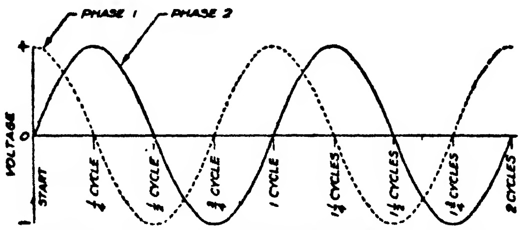


Fig. 8. Voltage Waves Generated by Two-Phase Generator—A Two-Phase Voltage Curve

A two-phase circuit in reality is two separate single-phase circuits, each with its own voltage wave impressed upon it. These two equal voltage waves are 90 degrees apart and always maintain this relationship. Fig. 7 shows a simple two-phase generator with the two separate windings 90 degrees apart rotating on the same shaft. This also shows the required two sets of slip rings and the

independent circuits 1 and 2 having absolutely no electrical connection with each other. The voltage waves produced by this generator are shown in Fig. 8. These are 90 degrees apart at the start and always maintain this relationship because the coils in the

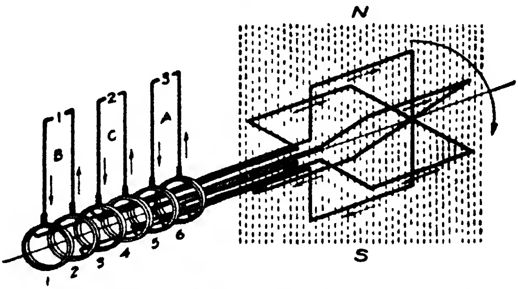


Fig. 9. Elementary Three-Phase Generator with All Six Leads Brought Out

generator generating the electromotive forces are set at the same angular displacement and cannot shift position.

A three-phase circuit is one in which three separate equal voltage waves are impressed 120 degrees apart on three circuit voltages. These may function on six wires but three wires ordinarily make a three-phase circuit. Fig. 9 illustrates a three-phase

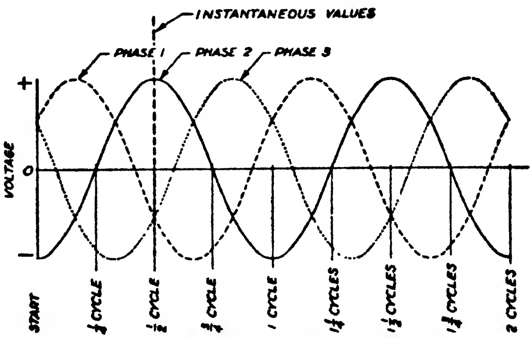


Fig. 10 Voltage Waves Generated by a Three-Phase Generator—A Three-Phase Voltage Curve

generator with all leads brought out to six-slip rings making a six-wire three-phase circuit. This is in reality three separate single-phase machines operating in the same magnetic field which makes all voltages equal. These circuits are often referred to as phases *A*, *B*, and *C* especially in line work and armature winding in order to

keep connections in correct order. The voltage waves shown in Fig. 10 show the relationship and position of the various voltages in a three-phase circuit. Because of the 120-degree spacing of the coils on this generator, all three voltage curves remain this same distance apart as shown in Fig. 10. A three-phase circuit has this particular characteristic. The instantaneous value of the voltage on one phase will be exactly equal to the algebraic sum of the voltages on the other two phases. Take the point where phases 1 and 3 cross below the line.

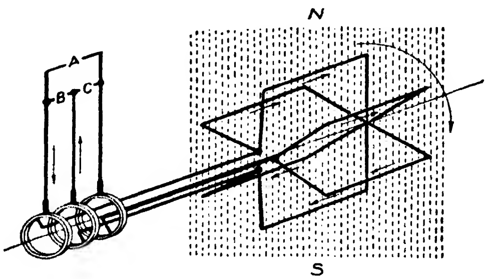


Fig. 11. Three-Phase Generator with Usual Internal Connections and Three Leads Brought Out

Measure this distance, and it will be found to be just half the distance to phase 2 above the line. This means that the sum of the two negative voltages on phases 1 and 3 will just equal the positive voltage on phase 2. All other points will give identical results at any position checked.

Because of this voltage condition on a three-phase circuit, the coils can be connected together inside the generator making only three slip rings necessary as shown in Fig. 11. This arrangement of coils enables each line to be a part of two phases as shown by *A*, *B*, and *C*, and each ring serves two coils in the generator which is standard in winding practice.

The other meaning of the term phase has to do with current and voltage relations within the circuit itself. When a load having ohmic resistance only is connected to a source of alternating-current voltage, the current wave will follow the voltage wave instantly, which means that current will be zero when the voltage is zero and reach a maximum value when the potential is at the peak, as shown by the curves in Fig. 12. The current and voltage are said to be *in phase* when this relationship exists.

A very few alternating-current electrical circuits have only ohmic resistance opposing the flow of current in them. Inductance or capacity, and in some cases both, are present along with the ohmic resistance to limit the flow. Inductive reactance is caused by the magnetic effects set up when alternating current flows in

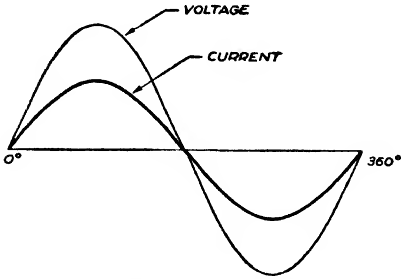


Fig. 12. Voltage and Current in Phase in a Single-Phase Circuit

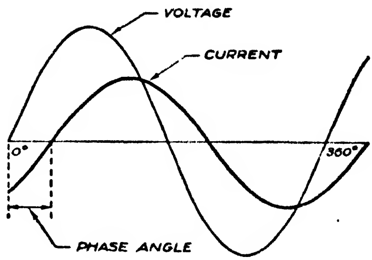


Fig. 13. Voltage and Current Out of Phase in a Single-Phase Circuit

coils with an iron core such as are found in transformers, motors, and choke coils. This inductive effect from the alternating magnetic field acts like counter electromotive force on the flow of current and delays the time when it reaches a maximum value. Whenever this condition exists in a circuit, the current is said to be lagging behind the voltage and is *out of phase* as shown by Fig. 13. In this case the voltage and the current do not pass through zero or reach a maximum value at the same time. The current passes

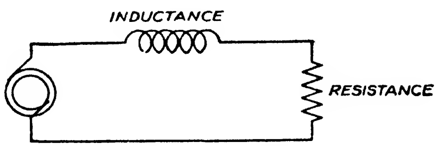


Fig. 14. Choke Coil and Resistance in Single-Phase Circuit Producing Effect Shown in Fig. 13

through zero at a later time and reaches a maximum later than the voltage maximum. The angle between them, measured along the horizontal line between the points where the curves cross it, is called the *phase angle* between the current and the voltage. The cosine of this angle is the *power factor* for the circuit. Fig. 14 shows a choke coil in series with resistance connected to a source of alternating current producing the effect shown in Fig. 13. All three

types of opposition to current flow, whether it is ohmic, inductive, or capacity, are measured in ohms. These combine differently in an alternating-current circuit than the ohms of a direct-current circuit. Inductive ohms and capacity ohms act at right angles to the resistance in the circuit when both are present. Fig. 15 shows three conditions which may exist in an alternating-current circuit. In Fig. 15 at *A* is illustrated the relationship existing in a circuit of the type shown in Fig. 14. The three sides of the triangle are made from the following: the base *R* is the ohmic resistance, the

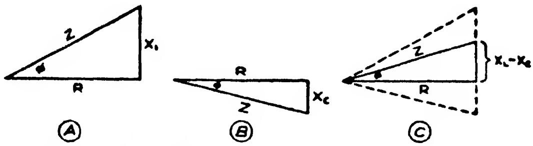


Fig. 15. Triangular Relations of *A*—Resistance and Inductance; *B*—Resistance and Capacity; and *C*—Resistance, Inductance, and Capacity. These control the current flow in an alternating-current circuit

altitude X_L is the ohms reactance due to the magnetic effect, and the hypotenuse *Z* is the *impedance* or actual resistance to the flow of current in this circuit. In all mathematical calculations involving Ohm's law in alternating-current circuits, the current is obtained by dividing the volts applied to the circuit by the impedance. Impedance in each case must be found from the triangle developed in Fig. 15 at *A*, *B*, or *C* as the circuit conditions demand. In Fig. 15 *B* shows how capacity and resistance combine to control the current flow when capacity is present. *C* illustrates the combined effects on the impedance of a circuit having resistance, inductance, and reactance. The magnetic and capacity effects are 180 degrees apart and neutralize each other leaving only the difference to combine with resistance to form impedance. Because of this neutralizing action between capacity and induction, it is possible to change the power factor of any alternating-current circuit. On account of these magnetic effects, capacity in the form of static condensers or synchronous condensers is used to correct poor power factor.

The phase angle ϕ between the impedance and the resistance in Fig. 15 is the same as the angle between the current and the voltage in Fig. 13, because the current lag is caused by the same magnetic effect which determines the size of the angle ϕ in the triangle.

POWER FACTOR

Power factor is the ratio of true power to apparent power. It is the wattmeter reading divided by the apparent power. The apparent power is the product of the ammeter reading multiplied by the voltmeter reading. This division gives the power factor, because the triangle of real watts and apparent watts is similar to the impedance triangle shown in Fig. 15.

The power triangle shown in Fig. 16 is made from the volts and amperes which are the apparent watts in the circuit and the wattmeter reading. The magnetizing power may be measured with a

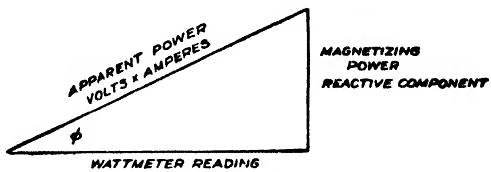


Fig. 16. Power Triangle of an Alternating-Current Circuit

reactive meter or may be calculated from the two previous sets of readings in the same way that the sides of any right-angled triangle may be found. Or the angle ϕ may be found from a table of cosines, as the wattmeter reading divided by the apparent watts gives the cosine ϕ. A protractor is used to lay off the angle and the magnetizing power is determined. This is a graphic method often used as a check on mathematical calculations. The reason these triangles are similar is due to the fact that inductance in an alternating-current circuit divides the current and voltage into two components, one acting on the resistance to produce useful work, and the other acting on the reactance to overcome the magnetic conditions in the circuit shown in Fig. 14.

TYPES OF WINDINGS

An alternating-current generator is a machine used to produce alternating current. It is made with three different types of windings to produce single-phase, two-phase, or three-phase current, depending upon what application is to be made of the power derived from the machine.

Direct current is almost always employed for exciting the

fields of alternating-current generators or synchronous motors. These direct-current exciters may be separately driven or mounted on same shaft as the alternator. Separately driven exciters are preferable, because they give more stable voltage conditions than the direct-connected machines. Exciters mounted on the same shaft with the main generator cause double the voltage variation with a change in speed as a separately driven unit, because an increase in speed will not only raise the alternator voltage but will increase the exciter current through the field. Thus a one per cent rise in speed

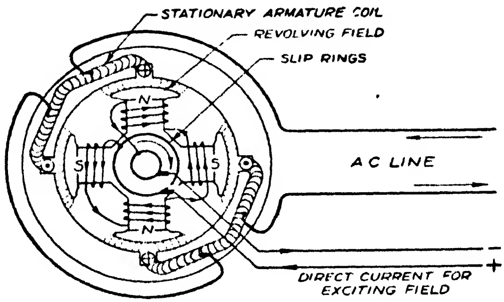


Fig. 17. Single-Phase 4-Pole Revolving Field Type of an Alternating-Current Generator with Only One Group of Coils

will not only raise the alternator voltage one per cent but will at the same time increase the field one per cent which would make two per cent change on the main line voltage. Separately driven units are more flexible in a large plant as one exciter may be made to supply the field for one or more generators, or exciters may be operated in parallel with other direct-current machines doing the same service.

Single-Phase Alternator. As explained in the earlier pages of this lesson, a single-phase alternator is made with but a single winding in the part connected to the line and supplying power. The field may be made with any number of pairs of poles. Fig. 17 illustrates a single-phase, 4-pole, revolving field type of alternating-current generator. The moving parts of alternating-current machinery are nearly always referred to as the *rotor* while the stationary part is called the *stator*. The slip rings supplying the field are connected to some source of direct current. There is but a single set of coils on the stator and hence only one source of voltage which

makes this machine a single-phase alternator. In many cases a three-phase generator is so connected that two-thirds of the coils are used for a single-phase machine. This arrangement will permit the machine to deliver 65 per cent of its three-phase capacity.

Any machine operating as a single-phase alternator should be very carefully laminated throughout its magnetic circuit to reduce iron losses, and the pole shoes should have a heavy squirrel cage

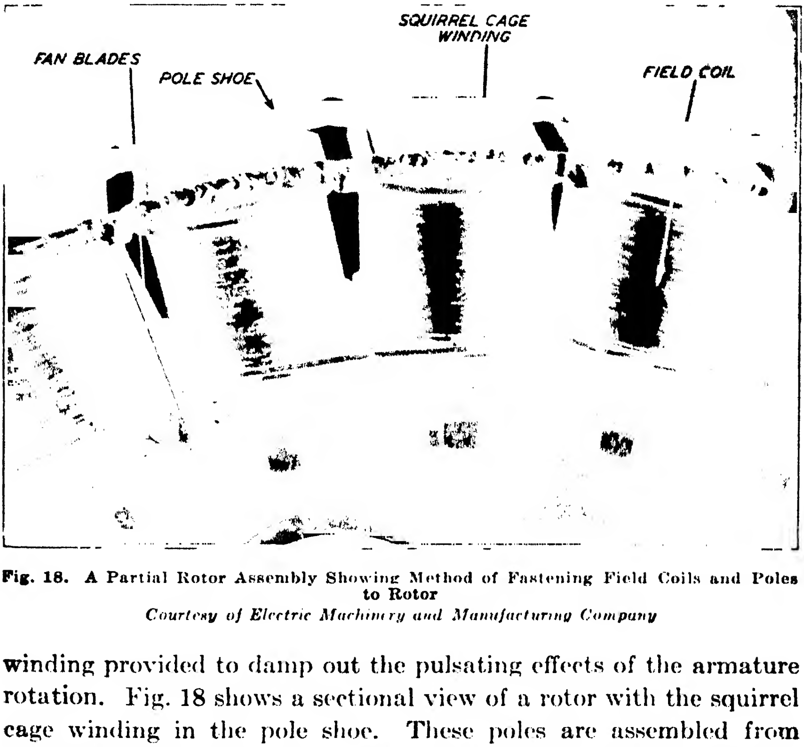


Fig. 18. A Partial Rotor Assembly Showing Method of Fastening Field Coils and Poles to Rotor
Courtesy of Electric Machinery and Manufacturing Company

winding provided to damp out the pulsating effects of the armature rotation. Fig. 18 shows a sectional view of a rotor with the squirrel cage winding in the pole shoe. These poles are assembled from their laminated punchings riveted together under hydraulic pressure. The squirrel cage or damper winding is welded on each side to insure a low resistance circuit completely around the rotor as this greatly increases the effectiveness of this type of winding.

For the same kilovolt amperes output, single-phase generators are fully 65 per cent heavier than a polyphase generator of the same power factor, speed, and voltage. This makes them not only more expensive to build, but increases all other investment costs.

Single-phase generators find application in electrochemical processes and some railway systems use single-phase power. Welding transformers and electrical furnaces use single-phase generators, so power sometimes has to be supplied for these particular applications where access to a power company line is not convenient. They also find some service in testing and experimental work.

Single-Phase Two-Wire System. The single-phase generator connected to a line gives the two-wire system as shown in Fig. 17. As alternator voltages are usually higher than secondary distribution voltages, a transformer is required between the generator and the load. The voltage used on a two-wire system is usually 110 volts and alternators generate 220, 440, 1300, 2300, 4000, 6600,

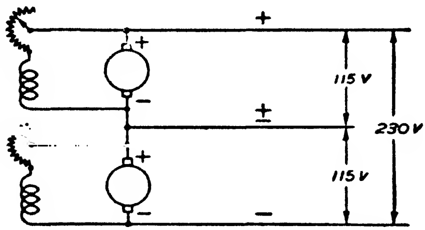


Fig. 19. Edison Direct-Current Three-Wire System

13,200 and a few 33,000 volts. The transformer ratio to produce 110 volts on the line will depend upon the voltage at the source.

Single-Phase Three-Wire System. The single-phase three-wire system has the same advantages for alternating-current systems as obtained with the three-wire direct-current systems discussed in Lesson 28. It is usually obtained on an alternating-current line by using a center tap on the secondary winding of the transformer. This method of obtaining the three-wire system has the added advantage of being able to handle any amount of unbalance there might be, whereas, the balancer systems are definitely limited in ability to handle over a certain per cent of unequal load.

Edison System. The Edison three-wire system for direct current was originally developed and used by Thomas A. Edison. He connected two 2-wire generators in series and connected the middle wire to the center point of the two machines as shown in Fig. 19. This arrangement provided two voltages, one for light and the other for power and, at the same time, cut down transmission losses. Any

amount of unbalance in the load is taken care of without additional equipment. However, too much unbalance causes an excessive voltage on the side of the line with the smaller load. A similar system is used for alternating current from taps on transformer windings.

Two-Phase Alternator. The two-phase generator is exactly like the single-phase alternator except that it has two separate windings on the stator. These windings make two entirely separate electrical circuits which have no connection with each other. The second winding, phase two, is spaced exactly between the coils on the

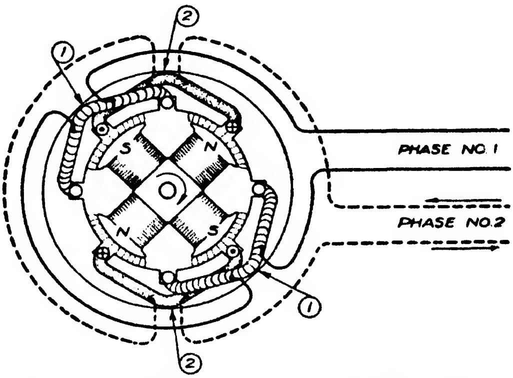


Fig. 20. Two-Phase 4-Pole Revolving Field Type of an Alternating-Current Generator with Only Two Groups of Coils

generator in Fig. 17. With the poles in the position shown in this figure, the voltage on *phase 1* would be at a maximum as illustrated by the voltage at the start in Fig. 8. At this instant the voltage on *phase 2* is zero because the pole flux is not cutting the coils on this phase at this instant. The position of the poles one-eighth of a revolution later, Fig. 20, indicates that the voltage on *phase 2* is maximum and *phase 1* has decreased to zero. This condition is shown in Fig. 8 at point marked ¼ cycle. Because these curves are 90 electrical degrees apart and always remain in this relative position, the two-phase system is sometimes called the *quarter-phase* system, this being just one-fourth of a cycle which is 360 degrees.

Four-Wire System. An inspection of Fig. 20 shows four wires required to complete each of the circuits for the two phases. Whether these circuits are used for supplying power for lights or motors, they

are complete and independent throughout with the voltages remaining on the quarter-phase angle with reference to each other.

Three-Wire Two-Phase System. The two-phase four-wire system may be converted to a three-wire system by making one line wire common to both phases or circuits. In order for this wire to handle the currents in both phases, the area of copper must be approximately 41 per cent larger than either of the other two. The current caused by the common wire is exactly the square root of two which is 1.41 times the current in either outside line.

The principal reasons for developing polyphase systems was

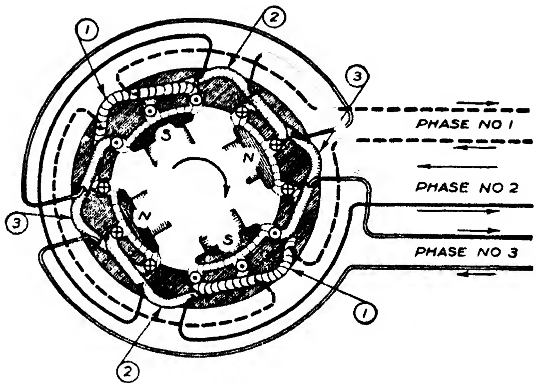


Fig. 21. Three-Phase 4-Pole Revolving Field Type of an Alternating-Current Generator with Only Three Groups of Coils

for the use of electric motors and savings in transmission costs. The early single-phase motor would run, but no means was known for developing torque for starting. Primarily, to meet this situation, two-phase systems were put into use. As soon as the three-phase circuit was discovered, its numerous advantages over a two-phase circuit made it so popular that very nearly all power systems changed over and the two-phase circuit has almost become history.

Three-Phase Alternator. The three-phase alternator is made by adding another phase to the two-phase machine. The addition of another set of coils makes a considerable difference in the voltage relations as will be seen from an inspection of the voltage curves shown in Fig. 10. The two-phase voltages were 90 degrees apart while these curves are separated by 120 degrees, which relationship is always maintained due to mechanical arrangement of stator coils.

This three-phase relationship is obtained by winding three sets of coils on the stator. They are practically always spaced 60 degrees apart, and one group is reversed so that the electromotive forces will be separated by 120 degrees. In Fig. 21 is shown a three-phase stator with the necessary three groups of coils. These are spaced exactly 60 degrees apart and all six ends brought out for each circuit. The pole position with reference to the different phases will give instantaneous voltages shown at the start of Fig. 10. The instantaneous voltage on phase two is at a maximum but is negative and is just starting toward zero, while the instantaneous voltages on phases one and three are both positive, but one is on the increase and three is already decreasing. This condition is explained from an inspection of Fig. 21. The two south poles are exactly under the coils in phase two producing a maximum negative voltage as shown by Fig. 10. The two north poles are partially over both phases one and three. As the rotor is revolving in a clockwise direction, the north poles are approaching phase one thus increasing the voltage positively, as shown in Fig. 10, and leaving phase three which causes a decrease in voltage as shown on the curve for phase three.

The leads to phase one have been reversed, which changes the voltage relations in the three phases from 60 degrees to 120 degrees. Windings for two- and three-phase stators are never wound, as shown in Figs. 20 and 21, this plan being used for simplicity in showing the phase relations. Factory windings for these machines would place sides of different coils in the same slot where the currents in the two sides would be in the same direction, as this arrangement gives more effective use of the iron. The diagrams become involved and difficult for the beginner to follow and understand the volutions in the various phases.

Six-Wire System. If all leads of the three-phase groups are brought out as shown in Fig. 21, six lines will be required and the system would be known as the six-wire system but would be only a three-phase system. This arrangement should not be confused with the conditions made by the windings of the ordinary three-phase alternator where six coil groups are used for each 360 magnetic degrees or pairs of poles. This coil arrangement would cause six different electromotive forces which would be 60 degrees apart or one-sixth of a cycle and would be known as a six-phase system.

If, however, the coil leads are connected either star or delta and three leads connected to the load, the resulting currents will differ in phase by 120 degrees. Thus an alternator may be either a three-phase or a six-phase machine depending upon the connections to the load.

Star-Connected-Four-Wire System. Figure 22 shows the coil groups in each phase connected together and the groups arranged at the 120-degree phase angle existing between each phase in the alternator shown in Fig. 21. Because of the fact that the instanta-

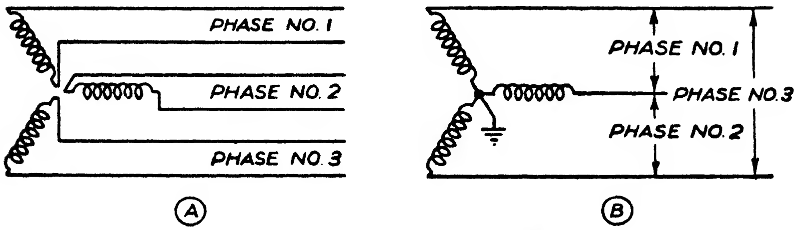


Fig. 22. *A*—Schematic Diagram of a Three-Phase Generator and a Six-Wire System; *B*—Three-Phase Generator Windings Y-Connected, Forming a Three-Wire System

neous value of voltage or current as shown by the curves in Fig. 10 is zero, each wire will act as a return for the other two. This makes possible the connection of the coil ends at the center of Fig. 22 at *A* which eliminates one wire from each phase and results in the wiring connection shown at *B*. A ground wire is frequently connected to the center tap and carried with the phase wires from the alternator through the whole distribution system. When this is done, the circuit is called the four-wire three-phase system.

The star connections of the coils, shown in Fig. 22 at *B*, places two groups of alternator coils in series for a one-line phase at the angle of 120 degrees. This results in a higher voltage on the line by the square root of 3 or 1.73 over the electromotive force obtained from one group of alternator coils with the connections as shown at *A*. Thus the alternator would have a higher voltage output but a more limited current output with this connection, no gain in power being accomplished.

The four-wire system of distribution permits an increased load on a three-wire line of nearly 75 per cent. Higher voltage transformers and motors may be used with resultant savings. Where this system has been tried, it has proved very satisfactory and ap-

parently no more hazardous with a good ground network than other grounded systems. A power company having a three-wire ungrounded system can, by increasing the generating capacity, changing the transformer connections, and using the fourth grounded wire, increase the total load on the lines practically 75 per cent.

Delta-Connected-Three-Wire System. Figure 23 shows the three coil groups for each phase in such a way that when they are joined

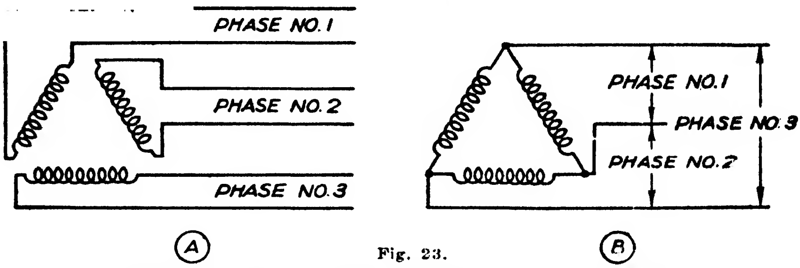


Fig. 23.
Three-Phase Delta Connection—Six Wires and Three Wires
A—Another Method of Showing a Three-Phase Generator Windings and a Six-Wire System; *B*—Three-Phase Generator Windings Delta-Connected, Forming a Three-Wire System

together they form a triangle or circular arrangement. Since there are 360 degrees in one cycle, this makes the three lines 120 degrees apart with reference to their phase relations. The delta connection gives the same voltage on each phase as the generator coil groups produce, but it increases the current delivered to the line by the square root of 3 or 1.73 due to the phase relationship.

The delta system is used extensively for transmission and distribution work. This connection is frequently used in winding induction motors as well as alternators. The power measured in kilovolt amperes is the same in an alternating-current generator regardless of the coil connection. With the star connection the voltage is higher by the square root of 3 and with the delta connection the current capacity is increased by the square root of 3 while the voltage remains at the single-phase value. Expressed mathematically, the power of the three phases of an alternator is: $P = EI \times \sqrt{3}$, where P is the power, E the voltage, and I the current for each phase as shown at *A*, Fig. 22. In the three-phase star-connected arrangement shown at *B*, Fig. 22, this becomes $P =$ (sq. root of 3) $\times E \times I$, where P is the three-phase power and E and I are the voltage and current the same as in the single-phase circuits. Power for the delta

connection is given by the formula $P=E\times$ (sq. root of 3) $\times I$ and applies to *B*, Fig. 23. Thus power is the same from an alternator regardless of which connection is used, but the star or Y connection delivers higher voltage to the transmission while the delta connection raises the amount of current which can be supplied, the voltage remaining the same as the single-phase potential.

CONSTRUCTION OF ALTERNATORS

Rating. The heating caused by the current in an alternator will determine its output. At normal voltage and normal current, a generator should not heat to a greater temperature than 40° C and should deliver its definite kilowatt rating at unity or 100 per cent power factor. Since the connected load determines the power factor at which the alternator must operate, its rating is usually given in kilovolt amperes, which is less than a kilowatt unless the power factor is unity. The rating if given in kilowatts is easily changed to kilovolt amperes by dividing the kilowatts by the power factor. A machine with a rating of 100 kilowatts would become a 125 kilovolt ampere rating at 80 per cent power factor. Ratings are frequently given in kilovolt amperes at 80 per cent power factor on the name plate of the machine.

Mechanical. Alternators may be made with revolving armature, where the generating coils rotate, or with rotating fields with the generating coils stationary. Practically all commercial machines use the latter construction while a few small alternators are built with moving coils. These require all the power current to be picked up with brushes on slip rings and more difficulty is experienced insulating the higher voltages found on the generating coils. Lighter moving parts cut down vibration with revolving field types and make machines with less weight per unit of output, all of which accounts for the preference shown for revolving field alternators.

The rotor or armature of the stationary field type of alternating-current generator is made by assembling laminations punched from special electric sheet steel. These punchings are varnished with special core varnish and assembled under pressure on a cast or steel spider to which they are securely fastened. Spaces are left when assembling to permit free circulation of cooling air. The coils on lower voltage armatures are wound with double-cotton or single-

cotton enamel magnet wire. These are then taped with cotton and oil linen tape, treated with waterproof and oilproof baking varnish, and dried in an oven at controlled temperatures. Slot insulation is made from a combination of insulating paper and varnished cloth.

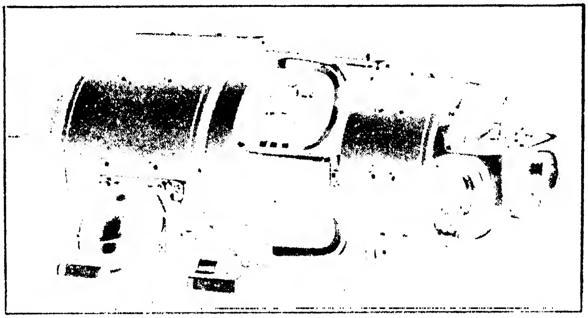


Fig. 24. An Alternating-Current Generator with a Direct-Connected Exciter
Courtesy of Imperial Electric Company

The coils are held in the slots with wood or fiber wedges which fit into dovetails in the teeth of the rotor.

The collector rings for revolving coil armatures are made of special bronze in order to improve wearing qualities and have low contact drop at the brushes. These rings must be thoroughly insulated from the rotor spider and yet be securely fastened to it. Fig. 24 shows an alternating-current unit made in capacities from

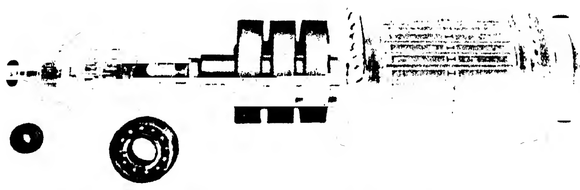


Fig. 25. Alternating-Current Winding on Rotor of Alternator (Right) and Direct-Current Armature of Exciter (Left) Mounted on Same Shaft
Courtesy of Troy Engine and Machine Company

1 to 150 kilovolt amperes with an exciter unit mounted on the main shaft. Fig. 25 shows the rotor element with the direct-connected exciter unit. Note the heavy-duty slip rings and the wedges holding the coils securely in the slots.

Armature Windings. The most important of several factors

which affect the arrangement of the windings used on an alternator are: (1) wave shape; (2) coil distribution; (3) winding costs; and (4) efficient generation of voltage. Some other features, such as number of poles and frequency, will be determined by the speed to be used, and will also have their effects on the armature windings.

The wave shape should approximate the sine wave, which would mean coil distribution up to certain limits. In order to obtain the required distribution to produce the desired wave shape, the coils must occupy several slots per pole per phase. These may be a whole number, but it is not necessary as 1½ slots per pole per phase may give a satisfactory wave form. Wave form is also frequently improved by using a fractional pitch winding. A fractional pitch winding is one which spans fewer slots than the pole covers which would make the coil sides somewhat less than 180 electrical degrees apart. This sometimes is reduced to .66 and even .5.

Distribution of windings makes better ventilation possible and helps reduce leakage reactance as well as improve the wave shape. However this is limited, particularly on high voltage machines, as more insulation must be used between layers in slots and less room is available for copper. End turns must also be more carefully insulated.

The cost of winding is an important item for consideration in constructing an alternator. Coils which can be formed and insulated before being placed in the slots very materially reduce costs and are better insulated. Form wound coils should all be the same shape. They require that the slots be open at the top, which reduces the efficiency of operation of the machine. However, these open slots may be closed or partially closed with magnetic wedges.

Efficient generation of voltage requires that the winding must be arranged so there is very little bucking action present. To avoid this trouble, the coils must be very nearly full pitch, that is, the sides must be approximately 130 degrees apart magnetically.

A careful analysis of the foregoing facts indicates that satisfactory winding of a machine will depend upon what is desired in the way of operating requirements such as wave form, efficiency and regulation as well as the first cost involved. Where conflicting variables occur, a compromise must be made which best meets the requirements. If the alternator is wound with three-phase windings,

these may be star- or delta-connected. In many cases there may be two independent groups of coils for each phase, especially with motor windings. Two sets of coils per phase make the machine easily converted into double normal voltage. A 220-volt connection can be made into a 440-volt winding by simply putting the groups in series.

Figure 26 shows a winding diagram for an alternator having 18

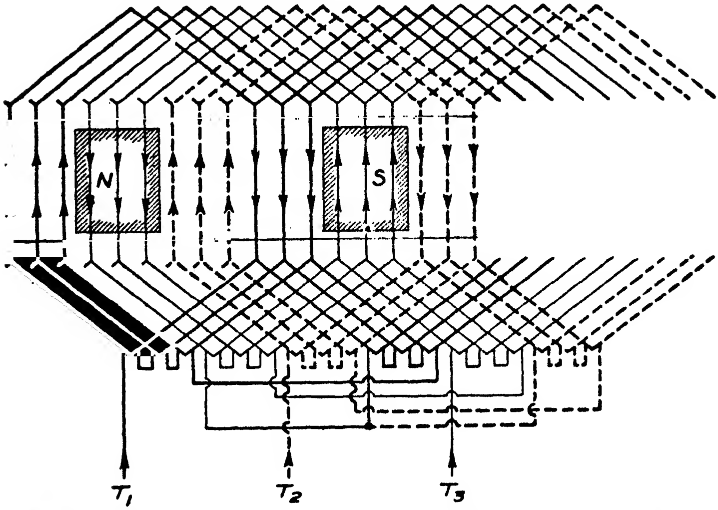


Fig. 26. Three-Phase Alternator Winding with 18 Slots, 18 Coils, 2-Pole Star-Connected

slots with 18 coils two-pole star-connected. This makes 6 coils per phase and 3 coils per pole per phase. The pitch is full being 1 and 10. Phase 1 is shown in light lines, phase two in heavy lines, and phase three in broken lines. This is a very simple connection and is shown to give the idea of the winding layout. In practice more coils would be used and the coils would be placed with sides of different coils in the same slot, as current directions are such in three phase as to permit this practice.

REVOLVING FIELD ALTERNATOR

The revolving field alternator is built in all types including the belt-driven, high-speed direct-connected steam engine, slow-speed type, Diesel engine, turbo-generator, and the water-wheel type.

Figure 27 shows a high-speed alternating-current generator made with either two or three bearings for belt drive or with one or two bearings where it is coupled to the prime mover. This unit is designed especially for use with oil, gas, or steam engine and built in capacities ranging from 12½ to 1250 kilovolt amperes 60-cycle with speeds from 514 to 1800 r.p.m. Note the open frame construction with the ducts at frequent intervals in the stator laminations. The air enters the machine through the end brackets, passes over the stator and field coils as well as through the stator core. This is accom-

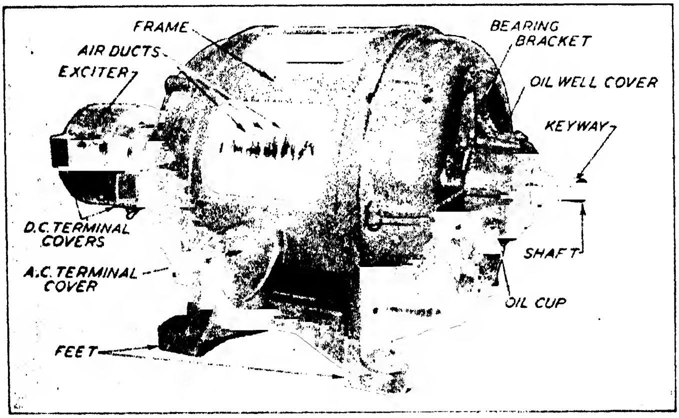


Fig. 27. Westinghouse Type G Alternating-Current Generator with Exciter Mounted on End of Generator

plished by an ample system of ducts and baffles which prevents recirculation of the heated air. A sealed type of sleeve bearing, made oil, vapor, and dust tight, reduces bearing wear to a negligible amount.

Stator. The stator frame of this machine is made of grey cast iron with the feet cast integral with the frame. The modern trend in all frame construction is toward rolled and welded steel frame construction. The core is built up with high-grade annealed steel sheet punchings dovetailed into transverse ribs in the frame. These laminations are compressed between end rings and keyed in place.

The coils are form wound from double cotton covered wire with the slot portions wrapped with fish paper and mica. This insulation is not affected by heat or moisture, and age has very little deleterious or harmful effect on its insulating qualities. Every stator is given a radio frequency test which indicates insulation defects on

individual turns. In this way the factory knows that each machine is free from defective coils. This defeats the chief cause of electrical breakdowns. Fig. 28 shows the high-frequency test being given to a large stator in process of construction.

Fig. 28. Testing Alternating-Current Windings with High-Frequency Alternating Current
Courtesy of Electric Machinery and Manufacturing Company

Rotor. The spider of the rotor is built up with steel punchings riveted together under hydraulic pressure. This core is then pressed and keyed to a steel axle shaft or a forged flange steel shaft for single bearing machines. The pole pieces are assembled from the electrical steel laminations riveted together under pressure. These poles are tightly dovetailed into rotor spider and keyed in position. The whole shaft and rotor is made with ample strength to withstand the variations in angular torque produced by Diesel engines.

The field coils are wound with copper straps or rectangular double cotton covered wire. As these are wound, an application of

insulating varnish is made to each layer and the whole coil is then impregnated with heat-resisting compound. Each coil is carefully insulated from the core and supports are provided to protect the coils against centrifugal forces and strains during operation. Fig. 29 shows a rotor used with the larger machines of this type. Note the damper winding provided near the pole faces to minimize hunting and variations in speed of certain types of prime movers. This addition to the rotor winding is almost a necessity where gas or

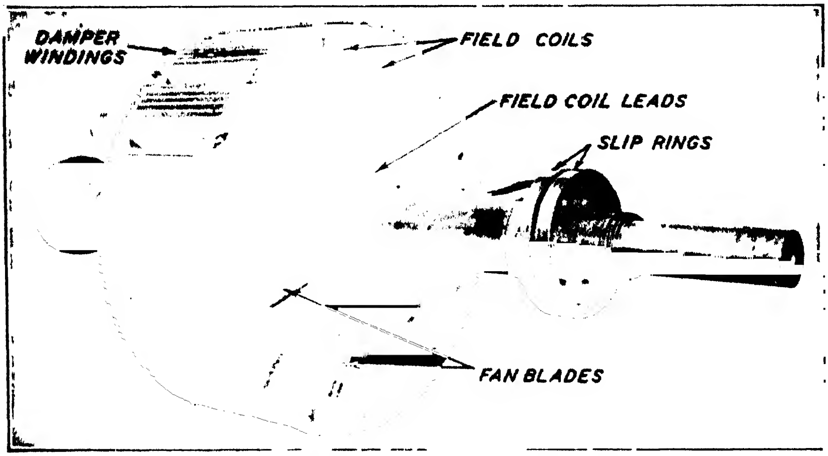


Fig. 29. Field Winding Mounted on the Rotor of a Large Alternator
Courtesy of Westinghouse Electric and Manufacturing Company

Diesel engines are used for motive power. Cast-iron collector rings are used almost exclusively on rotors magnetized from a direct-current source.

Exciters for these alternators are usually mounted directly to the frame of the generator with the exciter armature mounted on an extension of the rotor shaft. This eliminates the necessity for exciter bearings. In applications where direct-connected exciters are not desirable, any method of drive may be resorted to. Dual drive is frequently used in larger power houses with motor drive a highly favored method. Gas, steam engine, turbo, and water-wheel units are frequently used to power exciters. There are a few installations where V-belts are used from the main alternator shaft to the exciter.

SLOW-SPEED ENGINE-DRIVEN GENERATORS

The slow-speed generator is from necessity a massive piece of equipment with large weight per kilovolt amperes of output. Slow-speed machines require a larger number of poles to produce a given

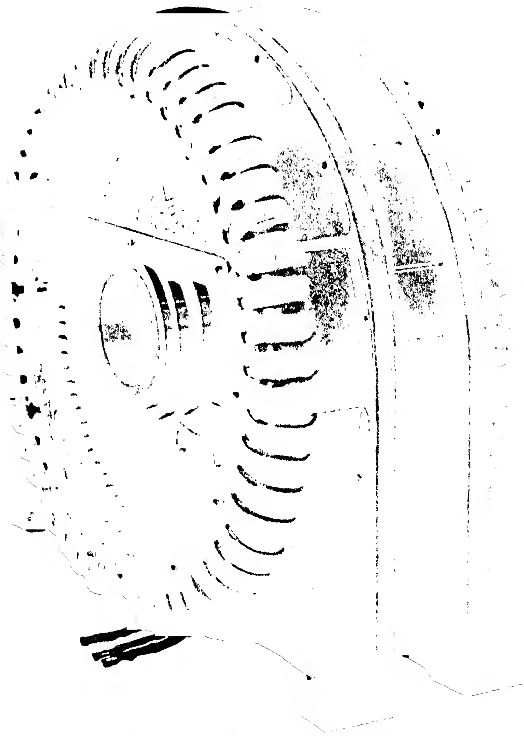


Fig. 30. Engine-Driven Type of Alternator. The Shaft and Bearings are Built as Part of the Engine
Courtesy of General Electric Company

frequency than is required with high-speed machines. In order to accommodate a large number of poles, the rotor diameter must be increased over what is required in more rapid moving elements. With slow moving field poles, larger sizes must be provided to furnish the magnetic flux necessary to generate the proper voltage. This leads to longer stator coils with increased iron in the stator.

Figure 30 gives an excellent idea of a slow-speed alternating-

current generator used in direct connection to a steam or Diesel engine. The open style frame provides ample opportunity for good ventilation. The end shields are die formed and thoroughly protect the windings without interfering with air circulation over the stator coils. A pole piece for this generator is shown in Fig. 31. The damper windings are located in the slots in the face of this pole piece. The cores for these poles are assembled in the same manner

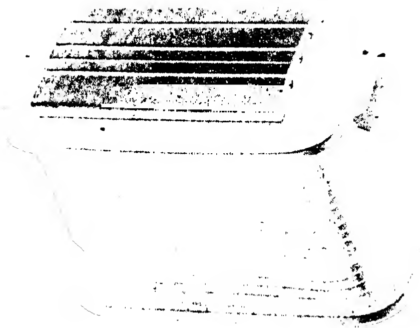


Fig. 31. The Pole of a Slow-Speed Engine Type Generator

as other field poles but are drilled and tapped for pole bolts. These poles are slightly spiraled on the rotor spider in order to reduce magnetic hum when the machine is carrying load. The field coils are wound with rectangular double cotton covered wire, as this shape increases the copper area of the coil. The usual treatment is given the coil to properly insulate it.

These rotors are supplied with or without damper windings depending upon the operating requirements the machine must meet. When these are supplied, they are made from either brass or copper bars embedded in the slots of the pole face, fitted into holes in the end rings and silver soldered under red heat. The silver solder forms a strong low resistance connection and has exceptional penetrating qualities. To facilitate pole removal, the end rings are made in sections.

DIESEL ENGINE GENERATORS

The Diesel Engine generator is of the slow-speed heavy construction type similar to the machine just previously discussed. Due to the more recent development of alternators for this type of drive,

the frame construction is nearly all fabricated, rolled and welded. The speeds of these machines very closely parallel those for the slow-speed engine type ranging from 257 to 450 r.p.m. Somewhat more rigidity must be put into the rotor shaft on account of the tendency

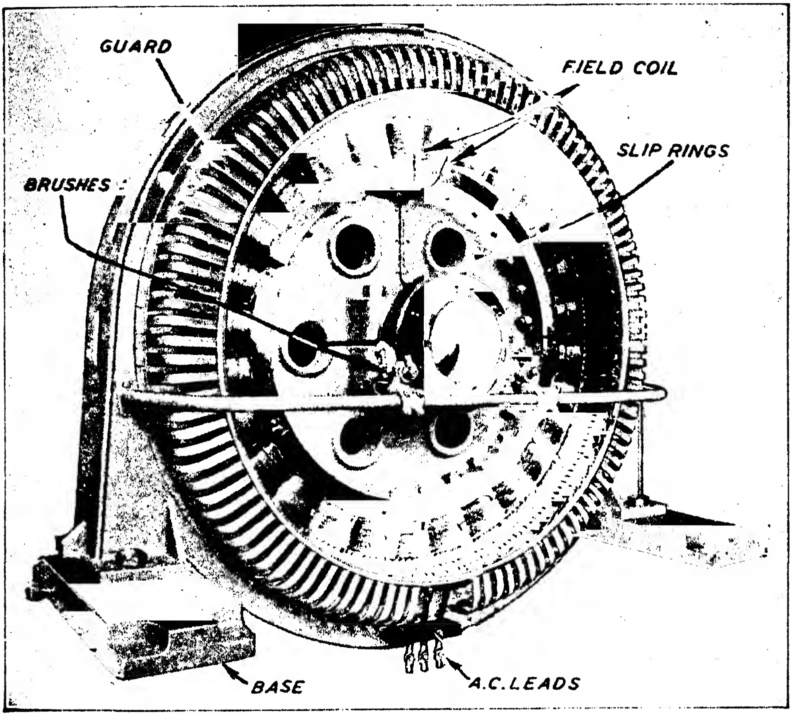


Fig. 32. A Large Slow-Speed Alternator to be Driven by a Diesel Engine
Courtesy of Electric Machinery and Manufacturing Company

of Diesel engines producing osciliating torque effects. Heavier damper windings are used on the poles to aid in smoothing out the engine torque when alternators are constructed especially for this prime mover. Fig. 32 shows a fabricated frame alternator built to operate with Diesel engine drive. Note the extremely heavy rotor flange to which the poles are bolted. The additional flywheel effect secured with this material is an aid to smoother operation of the unit. Even with the heaviest rotors, additional material is required to keep down the hunting tendencies of Diesel driven alternators. A heavy flywheel is usually provided

for this purpose. Fig. 33 shows a modern Diesel direct connected to an alternator with the stabilizing flywheel. Reciprocating steam engine driven generators have this same hunting tendency, but it is more pronounced in the Diesel so that heavier flywheels are required than are ordinarily used with steam units.

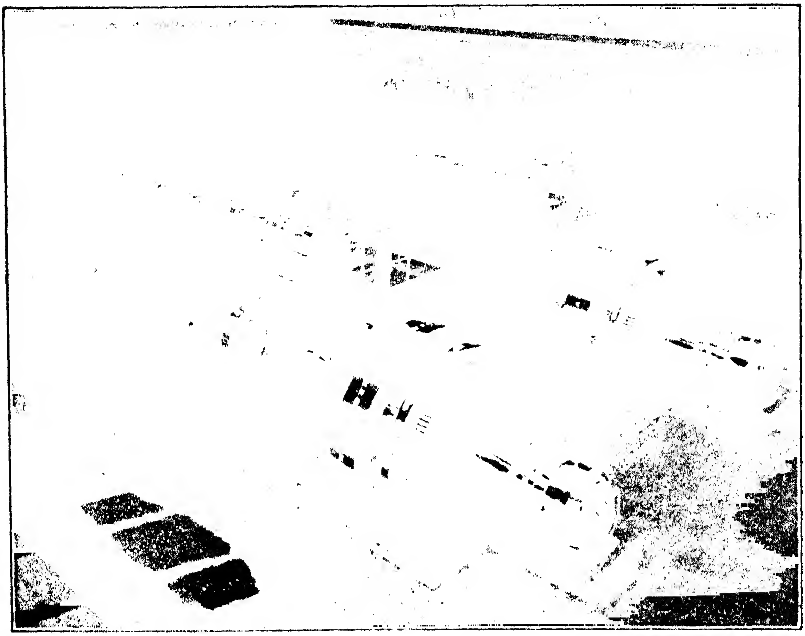


Fig. 33. A Diesel Engine Plant Consisting of Two Alternators with Direct-Connected Exciters
Courtesy of Electric Machinery and Manufacturing Company

TURBO-GENERATORS

Turbo-generators differ very materially in design and appearance from other types of generating equipment. The high speeds at which the rotating element operates requires a small diameter in order to reduce the stresses set up by centrifugal action. Noise and vibration set up by high-speed machines are muffled to some extent by totally enclosing the unit with sound deadening materials. In order to cool the equipment under these conditions, forced ventilation is resorted to. With the larger units this circulated air is washed and cooled before being blown through the alternator.

Many smaller units use reduction gears between the turbine element and the generator shaft. With geared units the generator can be of the standard belt-driven type. With capacities ranging from 10,000 up to 200,000 kilovolt amperes gearing would not be feasible. Fig. 34 shows a belt-driven type alternator connected to the steam turbine with reducing gears. Note the direct-connected exciter unit mounted on the alternator frame. Units of this particular type shown are made in capacities from 30 to 50 kilowatts.

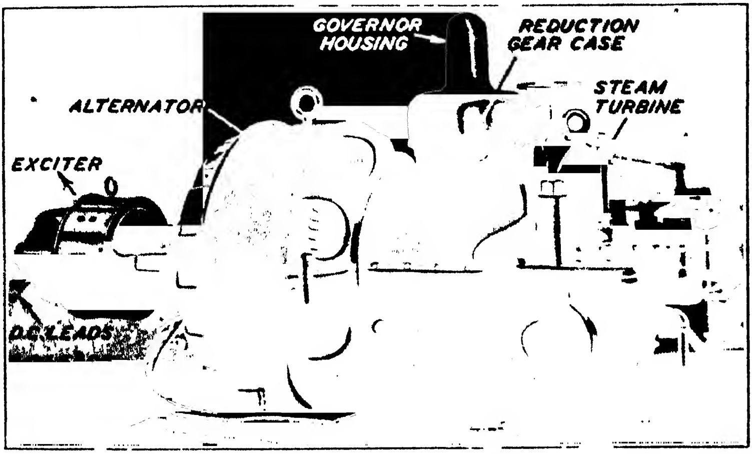


Fig. 34. A Medium Size Alternator Driven through Reduction Gears by a Small Steam Turbine
Courtesy of Westinghouse Electric and Manufacturing Company

The large high-speed direct-connected generators, Fig. 35, require a considerable change in the design from other types, especially in rotor construction. Note the totally enclosed features with arrangements for quick removal when cleaning and inspection are necessary. The pedestal-type bearing permits the rotor to be easily and quickly lifted from the stator with overhead crane should repairs be necessary on windings or bearings.

Stator iron and coil construction are not essentially different from other types of alternating-current generators. The iron is stacked so the slots are longer to accommodate the rotor poles. Coils are considerably longer with the straight sides imbedded in the stator slots wrapped with mica insulation. On account of the greater flexibility required at the ends of the coils these are wrapped with

treated cloth tape. Mica wrapped coils have greater dielectric strength, better heat conducting qualities, which improve reliability and efficiency for machines insulated with it. Better anchorage for the armature coils is secured through the use of insulated brackets. Adequate bracing is obtained by lashing the coils to these supports at frequent intervals.

Temperature detectors for checking the operating temperatures

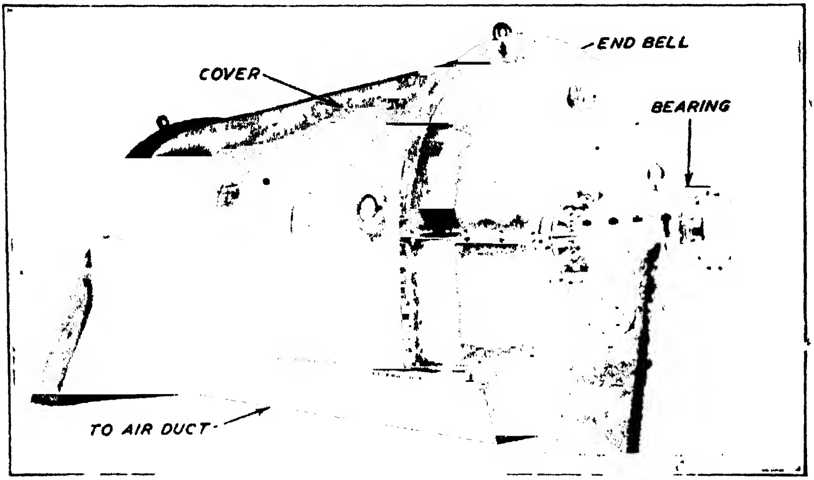


Fig. 35 A Large High Speed Horizontal Turbo Alternator Type of Generator
Courtesy of Westinghouse Electric and Manufacturing Company

are located in the stator slots at points where the heat is expected to be greatest.

The rotor, shown in Fig. 36, is machined from a solid steel forging. The slots for the field coils are machined radially to reduce noise from magnetic effects on the stator laminations. Field windings are made by forming continuous copper strip wound edgewise to form the coils. Metal wedges hold them securely in the slots. Mica strip is used between the conductors for turn insulation while moulded mica is placed between the coils and the pole piece. As the coils are made, each turn is given a treatment of special insulating varnish The end turns are securely braced and the rotor is finally baked at a high temperature during which time it is subjected to a very high pressure applied through the use of clamping rings. This treatment eliminates air spaces and forces

all excess binding material so the whole coil becomes an almost solid homogeneous mass.

Collector rings are made from a tool steel forging. These are then shrunk on a mica bushing which insulates them from a steel bushing pressed on the shaft. All joints and connections to these rings are silver soldered at high temperature to prevent loosening up under normal operation.

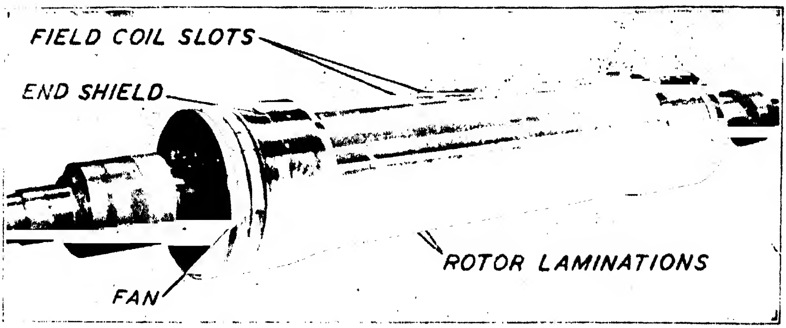


Fig. 36. Rotor of a High Speed Turbo-Alternator
Courtesy of Westinghouse Electric and Manufacturing Company

WATER-WHEEL GENERATORS

Alternators for use with water-power units are made in both vertical and horizontal types. A far greater percentage of water-wheel driven machines are for vertical drive. The slowest speed machines made are driven by hydro units. The 9000 kilovolt ampere units at Keokuk are only 58 revolutions per minute and the 5000 kilovolt ampere units at Niagara run 250 revolutions per minute. The units for use with low heads of water run slower than higher head machines. Fairly high speeds are used on water-wheel units, 300 to 600 r.p.m. being common in capacities ranging from 10,000 to 20,000 kilovolt amperes. Next to turbine driven units the water-wheel generators are the largest constructed, as capacities as large as 22,000 kilovolt amperes have been built in horizontal type and 45,000 kilovolt amperes in the vertical type.

Figure 37 shows one of the large slow-speed water-wheel generators in operation at Muscle Shoals. The stator design of these large machines does not vary greatly from other types of alternating-current generating equipment. In some of the larger machines, the

section of the coil in the slot is treated with bakelite and hot pressed. This process makes a more rigid coil which is less subject to damage to the strand insulation while the coils are being assembled in the stator.

Due to the wide range of speeds at which various water-wheel

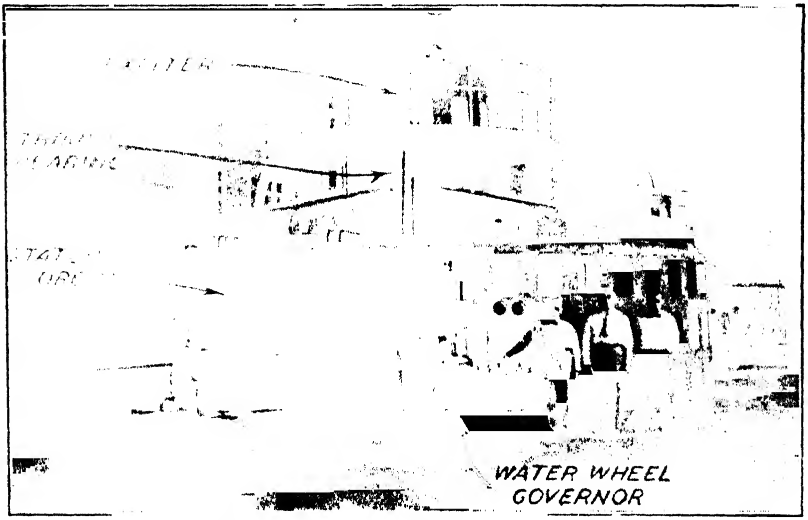


Fig. 37. A 25,000 Kv-a. Vertical Water Wheel Type of Generator
Courtesy of Westinghouse Electric and Manufacturing Company

units operate, no single design of rotor will meet all requirements. For lower peripheral speeds a fabricated steel spider is employed as shown in Fig. 38. The poles are either bolted or dovetailed to the rim, Fig. 39. For the moderately higher speeds laminated steel or steel plate is used. The large relatively high-speed machines have a laminated rim, Fig. 40, to which the pole pieces are dovetailed. The coils for the rotor poles are usually double cotton covered magnet wire for the smaller sizes and strap wound for the larger units, as shown in Fig. 39.

Many smaller hydro plants have been made for full automatic operation. Thermal protection is provided in the winding and bearings through relays which fully protect the units against overload or oil failure. In case of a shutdown the machines will go through the sequence of starting operations three times. If at this time the

trouble has not cleared, an attendant must visit the plant and clear the difficulty before the machine can be operated.

MOTOR GENERATORS

Motor generator sets are made in practically all capacities from fractional horsepower units used for supplying radio sets to 7000

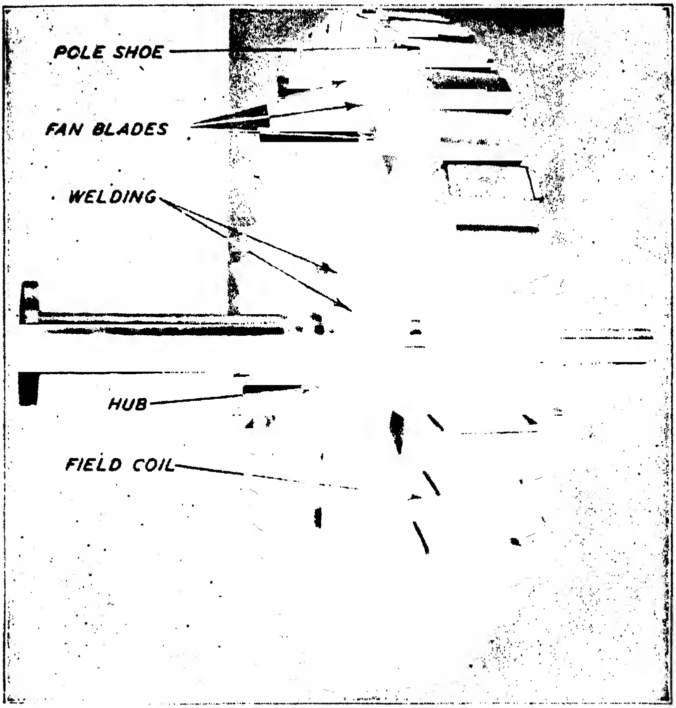


Fig. 38. A Rotor Built up by Welding Steel Plates and Angles. The Poles are Fastened to the Rotor by use of Dovetail Slots
Courtesy of Westinghouse Electric and Manufacturing Company

kilowatt sets used for large power applications. Some of these are used to convert alternating-current to direct-current while others change direct-current to alternating-current and some direct-current to direct-current where a change in voltage is desired.

A line of small motor generator sets has been made for producing alternating-current power to operate radio sets in locations where only direct-current power is available. Some of these were only 100

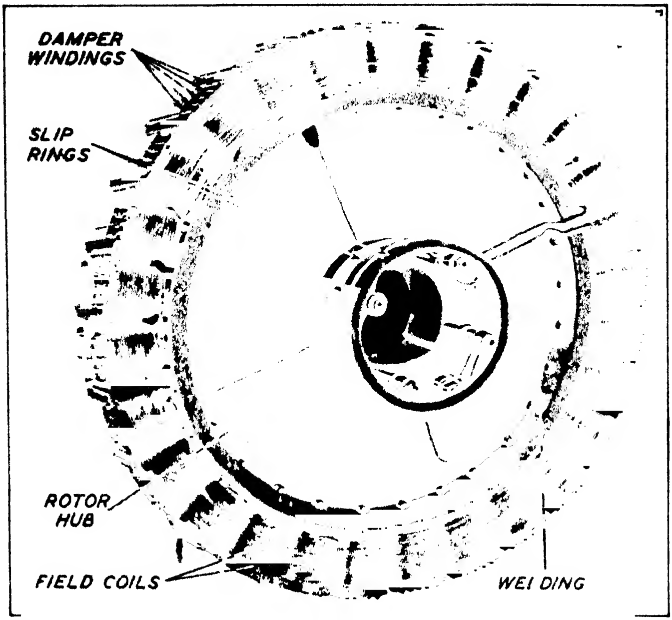


Fig 39 A Large Rotor with Damper Windings and Pole Pieces Bolted to Rotor
Courtesy of Westinghouse Electric and Manufacturing Company

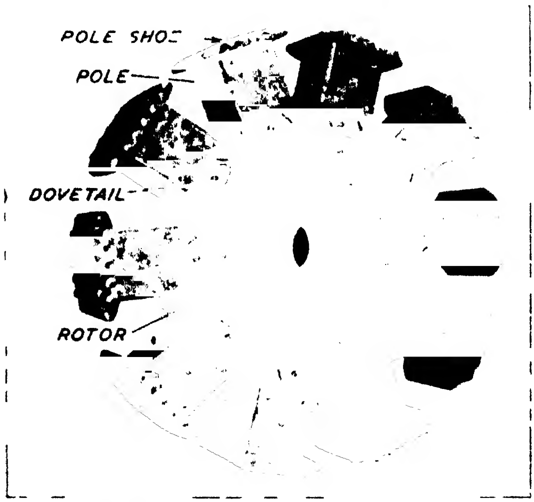


Fig 40. A Large High Speed Rotor with Pole Pieces Dovetailed to It
Courtesy of Westinghouse Electric and Manufacturing Company

watts for isolated plant use, usually 32 volts direct-current to 110 volts alternating-current. Others for hotel and similar service were one kilowatt units and operated on 115 volts direct-current to 110 alternating-current. All the radio sets in one section of a building would be operated from a single unit. Motor generator sets are rapidly being replaced by converters as they operate more efficiently and cost less to build than do motor generator sets. See Fig. 41.

HIGH-FREQUENCY GENERATORS

A line of high-frequency generators which will vary the frequency from 60 to 240 cycles is made in capacities from 5 to 100 kilowatt. These machines are sometimes referred to as frequency changers. A machine of this type is usually made from a slip

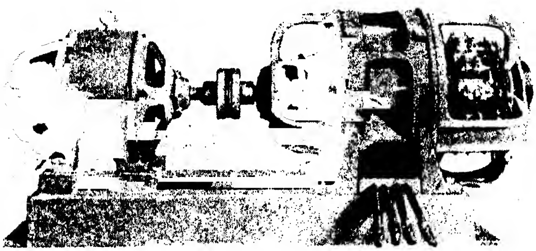
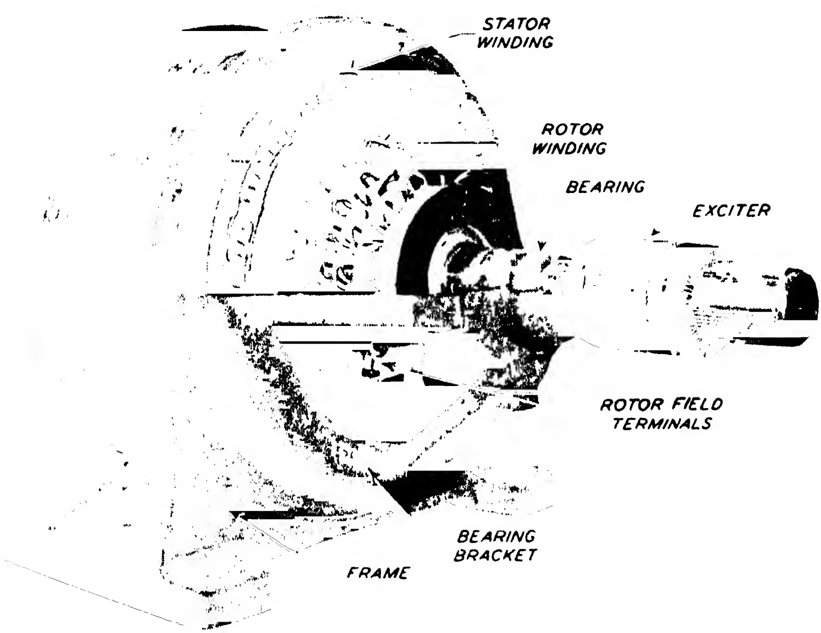


Fig. 41. A Motor Generator Set. An Adjustable Speed Direct-Current Motor Is Driving an Alternating-Current Generator
Courtesy of Reliance Electric and Engineering Company

ring motor preferably driven by a variable speed motor. The stator of the slip ring motor is connected to the line and the motor to be driven to the slip rings. The variable speed motor drives the rotor of the slip ring motor in the opposite direction from which the stator currents would rotate it. This will produce frequencies from the line frequency up to three times line frequency by 50 per cent over speed in the rotor; thus a 4-pole 60-cycle slip ring motor driven at 2700 r.p.m. will produce 180 cycles. A 2-pole motor connected to this frequency changer would have an operating speed of 10,800 r.p.m. Woodworking plants frequently require high-speed motors, and motor generator sets, arranged as described, produce the necessary speeds.

Machines have been made for producing very high frequencies, some as high as 500,000 cycles for operating induction coils. At the present time all new high frequency circuits are operated from oscillations set up by vacuum tubes. This method is proving so satisfactory that motor-generator machines are no longer advertised for this purpose.



A SYNCHRONOUS INDUCTION MOTOR AND EXCITER ARMATURE, WITH TOP HALF OF BEARING BRACKET AND EXCITER FRAME REMOVED TO SHOW THE DIFFERENT WINDINGS

Courtesy of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

ALTERNATING-CURRENT GENERATORS AND MOTORS

FOREWORD

The alternating-current system of power generation and distribution has been almost universally adopted since the invention of the transformer and the induction motor. The transformer has made possible the transmission of power over great distances with relatively low losses at high voltages and ready step-down to usable voltages at the point of use. The relative simplicity of alternating-current machines, both generators and motors, allows them to be produced at less cost than that of direct-current machines. In addition to the advantage of lower purchase price, alternating-current machines, because of their reduced number of parts, cost less to maintain.

FREQUENCY OF ALTERNATING-CURRENT SYSTEMS

In the early days of power-distribution systems and the manufacture of electric machines, a number of frequencies came into use because of lack of standardization and differences of opinion as to the best frequency from the standpoint of design. Consequently, frequencies of 25, 30, 40, 50, and 60 were used. Proponents of each system felt that certain advantages outweighed the advantages of standardization.

Design difficulties in machines of higher frequency were overcome as engineering and manufacturing technique advanced and the advantages of higher frequency became obvious. Since high frequency eliminates visible pulsation, thus improving lighting service, 60-cycle systems have become standard in the United States. The few remaining systems of lower frequency are rapidly being converted to 60 cycles to allow interconnection without the necessity of expensive frequency-changer sets at interconnecting points.

Therefore, purchasers of power will find 60-cycle systems available in practically every part of the United States. Anyone consider-

Photographs appearing throughout this section are by courtesy of General Electric Company.

ing the installation of an isolated generating plant should plan to use the 60-cycle system. The relatively greater availability of 60-cycle apparatus and devices, at lower cost, and the possibility of parallel or stand-by operation with purchased power warrants such a decision.

TYPES OF ALTERNATING-CURRENT SYSTEMS

Power will be derived from the incoming circuit of a power-distribution company or from one or more plant generators.

Single-Phase Type. The use of single-phase generators for general power is so infrequent that its principle will not be discussed here.

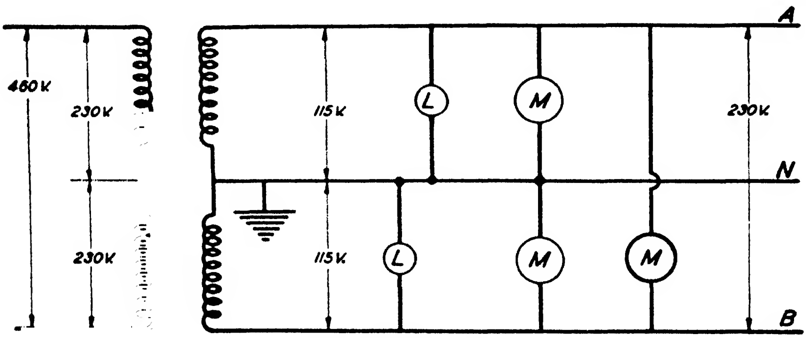


Fig. 1. Single-Phase, Three-Wire System

However, the derivation of single-phase circuits from a power-distribution system for lighting and for small motor loads is common. Single-phase generators are not used for large concentrations of power load, but may be used on small motor loads where the cost of running three-phase feeders to the motors would more than offset the higher cost of single-phase motors and slight added capacity in the single-phase line above requirements for lighting only.

Fig. 1 illustrates the use of an insulating-type, single-phase transformer with multiple primary and secondary windings in producing a 115/230 volt, three-wire system for lighting distribution. The same transformer with its primary coils in parallel may be connected across 230 volts, two-wire, to produce 115/230 volts, three-wire, on the secondary. As shown, lights and small motors are connected across 115 volts, and motors may be connected across 230 volts. Phase wires *A* and *B* need be large enough to carry the rated

output of the transformer, $I = \frac{kva}{V}$. Neutral wire N need be only large enough to carry the unbalance in load between two halves of

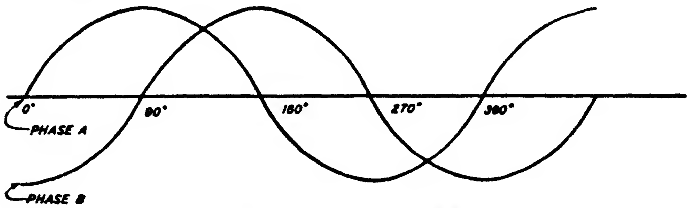


Fig. 2. Voltage Curves for Two-Phase Alternator

the three-wire system. The load between two halves should be divided as evenly as possible. In no instance should unbalance be such as to produce current in N in excess of 10 per cent of line current in A and B. Otherwise, neither the transformer nor line capacity will be utilized efficiently.

Two-Phase Type. Although gradually being replaced by three-phase systems, there are a number of two-phase distribution systems in use in this country. Two-phase may be derived directly from generator terminals or by transformation from a three-phase system to supply existing two-phase distribution systems.

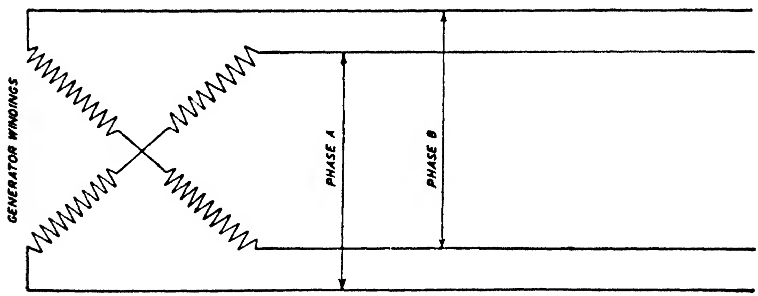


Fig. 3. Wiring Diagram for Two-Phase, Four-Wire Generator with Armature Windings 90 Degrees Apart

A two-phase alternator has two separate armature windings so placed that the voltage generated in each winding is displaced 90 degrees out of phase with the other. Fig. 2 shows the two voltages plotted with one-phase voltage leading the other by 90 electrical degrees. Since there are 360 degrees per cycle, one phase leads by

one-quarter cycle and, therefore, such units are sometimes called quarter-phase generators.

Fig. 3 shows the winding of a two-phase, four-wire generator. Voltages of phases *A* and *B* are equal. If the windings are connected so that one conductor of each phase is common, as shown in Fig. 4, we have a two-phase, three-wire system. When the mid-points of both windings of a quarter-phase generator are tied together, as on some machines, this system cannot be used. If the voltage of either phase is equal to E, then the voltage across the free ends of the interconnected phase will be equal to $E\sqrt{2}$.

In the vector diagram shown in Fig. 4, the two lines which repre-

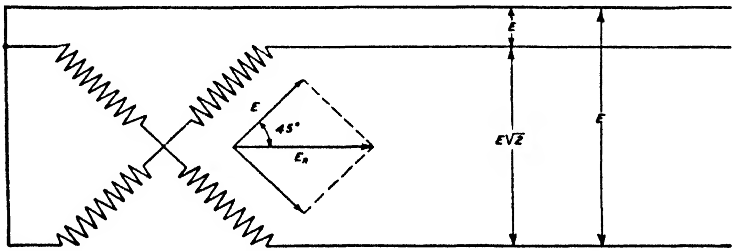


Fig. 4. Wiring Diagram for Two-Phase Generator Arranged for Three-Wire System

sent the voltages E are 90 degrees apart and form a right angle. A square can be formed by drawing the two dotted lines parallel to the lines E. In finding the length of the diagonal line, it is necessary to apply the law of the right triangle, which is as follows: The hypotenuse of a right-angle triangle is equal to the square root of the sum of the squares of the two sides adjacent to the right angle. Then considering the value of E to be 1, the value of E_R is equal to the square root of $1^2+1^2=\sqrt{1+1}=\sqrt{2}$ which is 1.414. Therefore, $E_R=E\sqrt{2}$.

The current in any wire of a two-phase, four-wire system is

$$I=\frac{kw}{2E}$$

in which kw is capacity of generator; E, voltage of phase A or B. The current in the common or neutral conductor of a two-phase, three-wire system is $\sqrt{2}$ or 1.414 times the current in the other conductors with balanced load.

If it is desired to produce a two-phase, four-wire circuit from a three-phase, three-wire system, Scott-connected transformers may be used, as shown in Fig. 5. In a two-phase system, since the phase

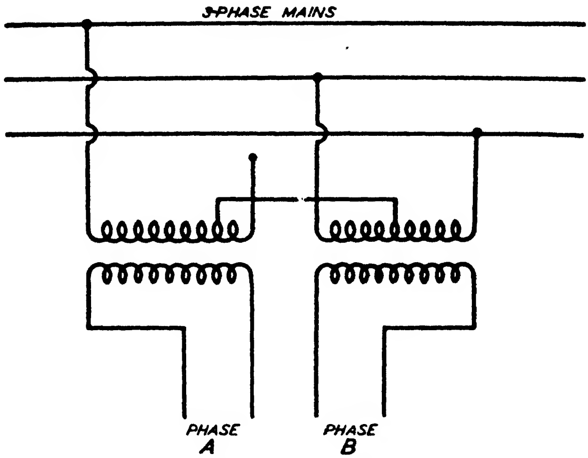


Fig. 5. Three-Phase to Two-Phase Transformation by Scott Connection of Transformers

voltage is generally 230 volts or 460 volts, a lighting circuit is obtained by use of a single-phase 115/230 volt, secondary-winding transformer.

Three-Phase Type. Three-phase generators have their armature windings divided into three sets of coils so arranged as to produce

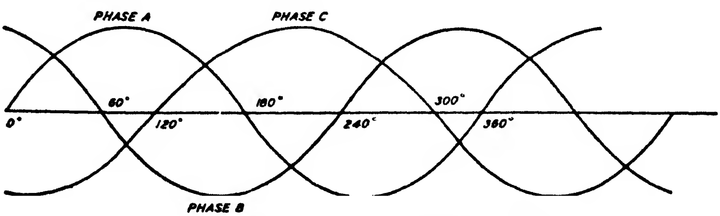


Fig. 6. Voltage Curves for Three-Phase Generator

electromotive forces 120 degrees apart, Fig. 6. Armatures may be either Y- or Δ-connected, Figs. 7 and 8. In a Y-connected system the line voltage E_R is greater than the voltage produced by that particular phase-winding, as is shown by the vector diagram in Fig. 7. By the use of trigonometry, the line voltage E_R has been found to be

equal to the phase voltage times the square root of 3 or 1.732 E. The current in each line wire is the same as the current in each phase winding.

In a Δ-connected system, the line voltage is the same as the phase

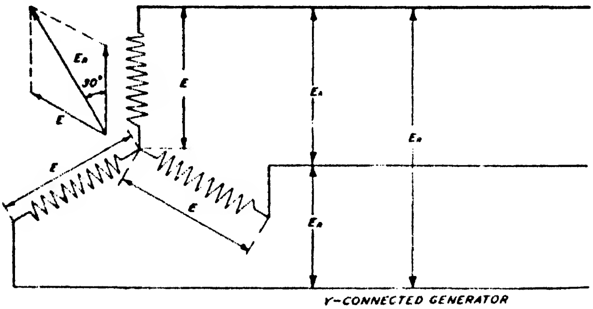


Fig. 7. Wiring Diagram for Y-Connected Three-Phase Generator

voltage, but the current per line is the $\sqrt{3}$ times the current per phase. In either system, star (Y) or delta (Δ)

$$W = EI\sqrt{3}$$

for a noninductive circuit, in which W is watts output, E is pressure in volts, and I is current in amperes.

For an inductive circuit whose power factor is less than unity

$$W = EI\sqrt{3}\cos\theta$$

in which $\cos\theta$ is power factor.

When using transformers, a three-phase, three-wire circuit may be produced by use of two single-phase transformers with secondaries

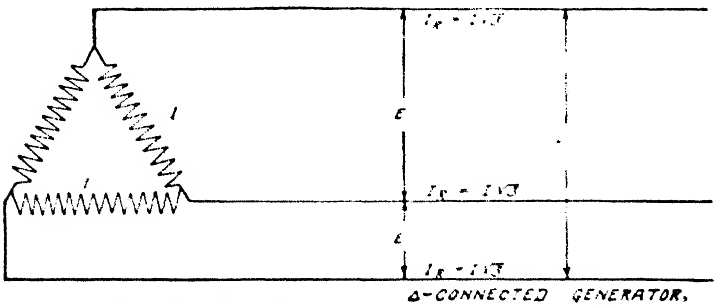


Fig. 8. Wiring Diagram for Δ-Connected Three-Phase Generator

connected in open delta. This allows minimum first cost with the possibility of adding a third single-phase transformer at a later date, if load builds up to demand it.

A major development in recent years is the three-phase, four-wire system of secondary distribution for buildings and manufacturing plants. Where large blocks of power are generated and distributed, it is common practice to ground the neutral or common point in a Y-connected generator or transformer, thereby creating a three-phase, four-wire system. This allows transmission at a voltage

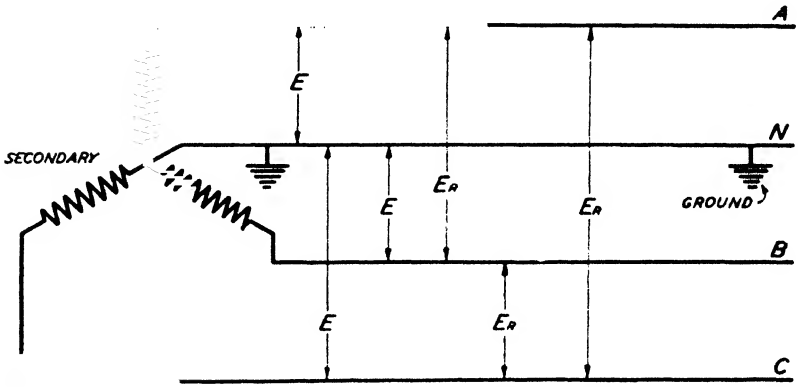


Fig. 9. Three-Phase, Four-Wire Distribution from Three Transformers. The Neutral Is Grounded

$\sqrt{3}$ (1.73) times the phase voltage of the generator or transformer windings, resulting in less copper loss and making possible the use of lower priced cable.

The most common voltage used on this system is 120/208 volts, Y-connected. It is derived from secondaries of three single-phase transformers with 120-volt secondary windings, Y connected, as shown in Fig. 9. In this system, the voltage from each phase to neutral $=E$ or 120 volts, and the line voltage, phase to phase, $E_R=\sqrt{3}\times E$ or 208 volts.

In practice, the three phase conductors and the neutral conductors are carried throughout the plant or building, the three phase lines being connected to 208-volt, three-phase motors. One or more phase wires and the neutral are used for lighting requirements. Connection from phase to neutral allows 120 volts for lighting and for

small motors, without the need of adding transformers to provide lighting circuits. The lighting load is evenly divided between phases and neutral so that the neutral conductor need be only large enough to carry the unbalance, never greater than 10 per cent.

System Voltages. The most commonly used distribution systems are at 4,000, 2,300, 460, or 240 volts, all three-phase, three-wire, and 120/208 volts, three-phase, four-wire circuits. Voltage selection depends on many factors including kilowatts of load to be distributed and distance to be transmitted. If a 2,300 or 4,000 volt distribution system is used, it is necessary to install step-down transformers at points of use of smaller motors and of lighting. This reduces the copper losses and permits use of smaller sizes of cable. A similar reduction is necessary for lighting purposes when a 460 or 230-volt system is used.

Small plants and buildings may be served by 460 or 230-volt, three-phase, three-wire circuits to motors with separate 115/230-volt lighting system, or by 120/208-volt Y three-phase, four-wire system. Generators can be selected to generate at any one of these voltages. The circuit can also be derived from step-down transformers.

Selection of a Distribution System. Unless some special consideration incident to existing equipment is required, the system selected should be 60-cycle, three-phase, and either 460/230 volt, three-wire, or 120/208 volt (Y), three-phase, four-wire. The final selection can be made only after a thorough study of all costs involved for a particular plant or building.

SELECTION OF GENERATORS

Modern alternating-current generators, sometimes called alternators, are constructed with a stationary armature or stator wound to produce single-phase, two-phase, or three-phase voltage, and a revolving field or rotor excited from a separate 125- or 230-volt direct-current source. Machines up to 1,200 r.p.m. have their field coils protruding from the rotor and are called the salient-pole type. See Figs. 10 and 11. On turbine type generators operating up to 3,600 r.p.m., the field coils are imbedded in slots of a cylindrical steel rotor to reduce noise and wind friction and to provide necessary strength for operation at high speed. The exciting current is brought to the revolving field through stationary brushes which run on

collector rings mounted on and insulated from the shaft. The terminals of the field winding are brought to these rings. In most instances, especially on generators 600 r.p.m. and above, the exciter is direct-connected to the generator shaft. The formula,

$$f = \frac{P}{2} \times \frac{\text{r.p.m.}}{60} \qquad (1)$$

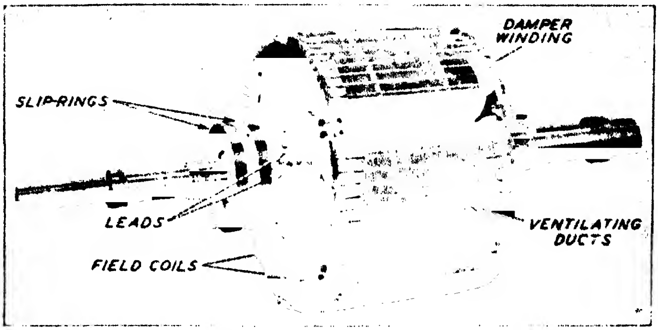


Fig. 10. Revolving Field for 250 Kva (150 Kw), 60 Per Cent Power Factor, 1,200 R.p.m. Generator

where

f = cycles per second (frequency)
P = number of poles (always an even number—2, 4, 6, etc.)
r.p.m. = revolutions per minute

determines the fundamental characteristics of all alternating-current machines, both generators and motors. Therefore, after the frequency of the system is known, the operating speed may be determined. Where frequency is, let us say, 60 cycles, the maximum synchronous speed of the machine will be 3,600 r.p.m., and so on down to 1,800, 1,200, 900, 720, 600 r.p.m., and so forth.

Let us assume that it has been decided to generate all or part of the power required in a particular plant or building. The most important problem at this point is to determine the size of the generating unit or units required. Generators are rated in kilovolt-amperes at 0.8 power factor or the resulting kilowatts—for example, 250 kva at 0.8 power factor or 200 kw—since it may be assumed that the average inductive load of motors will be 0.8 power factor, lagging or higher.

Generators are designed with fields and exciters of sufficient capacity to produce leading kva to offset the lagging kva of inductive loads and are sometimes rated 0.7 and 0.6 power factor or lower for special conditions.

Typical generators of small and medium size are rated as standard 125, 156, 187, 219, 250, 312, 375, 438, 500 kva and so forth, up to 1,000 kva in standardized steps. Standard ratings are based on 50°C. rise on the armature for continuous loading at rated kva.

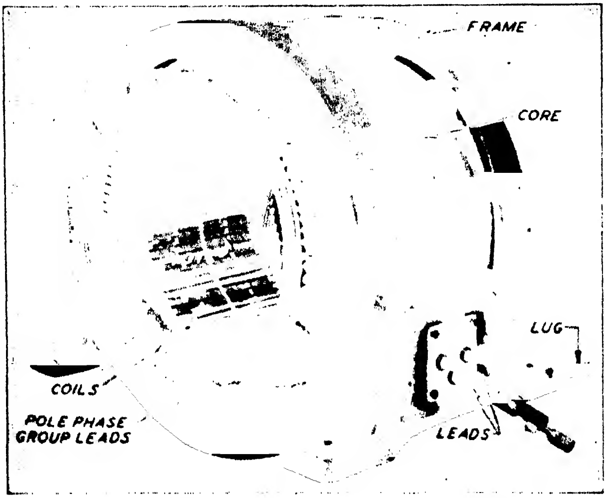


Fig. 11. Stator for 250 Kva (150 Kw), 60 Per Cent Power Factor, 1,200 R.p.m. Generator

Such generators are nominally rated machines. For special loading conditions, requiring overload for definite periods, a special rating may be purchased—for example, rated load 40°C. rise continuous, 25 per cent overload two hours, 55°C rise; or rated load 50°C. rise continuous, 10 per cent overload, two hours. The last-mentioned rating is standard for generators driven by Diesel engines.

The nature of the load will be taken into consideration when selecting the size of generating units. Only in rare instances will the load be constant over the entire operating period. It is probable that there will be an established minimum, for example, 200 kw, above which the load will increase during peaks. If, then, we establish 200 kw as the *base* load, we may pick a generator of that capacity

as the *base* generating unit, with additional unit or units to carry added load to peak requirements.

Since no generating unit can be considered indefatigable, it is necessary to plan for stand-by or spare generating capacity against the time when each unit must be taken out of service for periodic overhauling or repair. In anticipation of such times, the size of units for stand-by or peak requirements should be such that one or

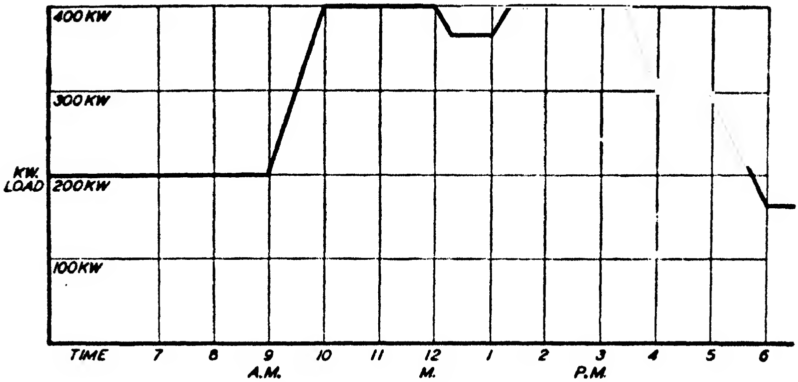


Fig. 12. Typical Plant Load

more of the stand-by units will carry the base load when the *base load* machine is out of service.

In Fig. 12, 200 kw is base load and 400 kw is maximum load. The base load generating capacity should consist of one 200-kw machine or two 100-kw machines, with an added 200 kw of capacity, either one or two machines, to take care of peaks. Considering the setup from the standpoint of stand-by capacity, one machine can be taken out of service, leaving 200 or 300 kw of generating capacity, which would allow operation at reduced output during a period of repair or overhauling.

Type of Prime Mover. The selection of the prime mover to drive the generator depends upon several considerations. For example, if suitable boiler capacity is available and exhaust steam is required for heating purposes or for process work in a factory, a reciprocating steam engine or, more probably, a non-condensing steam turbine may be desirable. The exhaust steam may then be utilized. In many instances, process steam at pressures higher than atmospheric pres-

sure are required. Then the modern steam turbine with facilities for extracting or "bleeding" at different pressures is best suited. Fig. 13 shows a 2,500-kw, 60-cycle generator direct-connected to a condensing type turbine.

Comparing these two types of steam-driven prime movers, the advantages of the turbine immediately become evident. Turbines operate most efficiently at higher speeds, 1,800 or 3,600 r.p.m., where-

Fig 13 Condensing Steam Turbine Generator Set (2 500 Kw)

as engines are inherently slow-speed. The combination of a high-speed turbine direct-connected or geared to a high-speed generator and exciter is a less costly and, at the same time, more efficient unit than the slower speed engine with its generator, usually direct-connected, and with a belted or separate exciter set.

During recent years, the internal combustion engine, notably of the Diesel type, has been developed to the point where it can be used efficiently as a prime mover for generators. Diesel engines are available in speeds ranging from 277 r.p.m. in larger sizes to 1,200 r.p.m. in medium and small capacities. Generators are built to direct-connect at any of those speeds. Fig. 14 illustrates typical construction of a generator and exciter for coupling to slow-speed engine.

In some cases, a combination of steam-driven and internal combustion prime movers may be desirable. For instance, during the winter months a turbine-driven generator may be desirable to furnish exhaust steam for heating purposes, with the added requirement of an internal combustion driven unit for peak loads. During the months that require little or no steam, the load may be carried by one or more internal combustion driven generators.

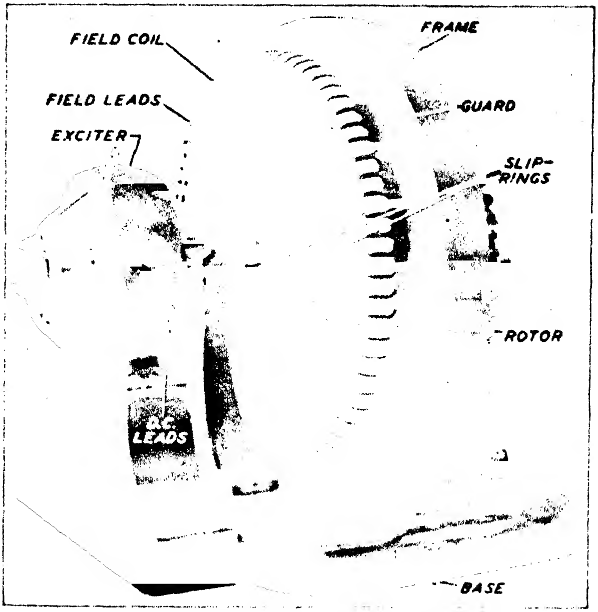


Fig. 14. A.-C. Generator with Direct-Connected Exciter (250 Kw, 360 R p m)

Mechanical Characteristics of Generators. The nature of enclosures, treatment of windings, and other related characteristics of alternating-current generators are similar to features described for direct-current generators. The same conditions dictate selection of different features regardless of the type of system—direct-current or alternating-current, single or polyphase alternating-current, etc.

SELECTION OF ALTERNATING-CURRENT MOTORS

Alternating-current motors are available in many types for operation on all commercial frequencies, 60-cycle predominating; for

single-phase and polyphase circuits; and in horsepower sizes for different system voltages, as indicated in Table I following:

TABLE I

Standard Motor Voltages and Horsepower

Single Phase			Two- and Three-Phase		
Voltage	Min Hp	Max Hp	Voltage	Min Hp	Max Hp
110 115 120	No min	1½	110 115 120	No min	15
220 230 240	No min	10	220 230 240	No min	200
440 550	5	10	440 550	No min	500
			2200 2300	40	No max
			4000 4160	75	No max

GENERAL CONSIDERATIONS

The following factors should be considered when selecting alternating-current motors.

Horsepower Rating. It is, of course, essential to select a motor capable of carrying the required load without overheating and resultant damage to insulation. Modern insulating materials allow a temperature rise on open motors of 40°C. (55°C. for enclosed motors) above an assumed ambient or room temperature of 40°C., or a total temperature of 80°C on Class A insulated motors. Where ambient temperatures higher than 40°C. are encountered, Class A motors with lower temperature rise, say 30°C., may be used as long as the total temperature does not exceed 90°C for enclosed motors. These limits may be raised to 110°C. total temperature for open motors and 115°C. for enclosed motors with Class B insulation.

Modern (so-called general-purpose) polyphase motors are not rated up to their maximum safe output, but have a service factor of 1.15 at rated voltage and frequency. For instance, if the load requirement is 22, instead of applying a 25-horsepower motor it is permissible to use a 20-horsepower motor, since 20×1.15 (service factor) = 23 horsepower, the permissible load, and is within the accepted safe limits of temperature rise for the insulation. However, the manufacturer's guarantees of efficiency and power factor, which are based on normal rating, do not apply in those instances where the service factor rating is used.

Loads which are fairly constant for long periods require motors rated at the maximum requirement. For example, let us assume that

the steady load for the greater part of the time may be 40 horsepower, but under certain conditions the load may rise to 49 horsepower for periods of 30 minutes or more. A 50-horsepower motor would then be required. This period of permissible short-time overload varies from 15 minutes to 2 hours for different sizes of motors, and such conditions must be referred to the manufacturer.

Special-duty cycles, involving large variations in load, accelerating, and retardation peaks, and periods of standstill require special calculation and should be referred to the manufacturer. A motor of correct thermal capacity and adequate torque to handle all loading conditions of the cycle will be selected. Too large a motor should not be applied—first, because of unnecessary cost, and second, because an underloaded motor produces poor power factor. (See Power-Factor Correction in this section.)

Altitude. Standard ratings of motors are applicable for altitudes not exceeding 3,300 feet above sea level. At higher altitudes, the temperature rise at rated load will increase approximately one per cent for each 330 feet increase in altitude. Special motors are, therefore, required to keep the insulation temperature within allowable limits.

Variation in Voltage and Frequency. The starting torque of all alternating-current motors varies with the square of the voltage impressed on the motor terminals. For instance, consider a motor wound for 220 volts and with rated starting torque equal to 200 per cent of the full-load torque. If the system voltage drops to 206 volts, the actual starting torque will be $\frac{206 \text{ squared}}{220 \text{ squared}} \times 200$ per cent or 175 per cent of full-load torque. Slight changes in frequency will affect only the synchronous speed.

In general, motors will operate successfully (without, however, meeting guarantees) where:

1. The variation in voltage does not exceed 10 per cent above or below normal.
2. The frequency does not vary more than 5 per cent above or below normal.
3. The sum of voltage and frequency variation does not exceed 10 per cent (provided frequency variation does not exceed 5 per cent)

above or below normal voltage and frequency rating as stamped on the motor name plate.

Standardization and Safety. Motors and control must conform to local and national standards in order to (1) be allowed connection to the power circuit, (2) satisfy safety and fire underwriter requirements, and (3) allow lowest possible insurance rates. Recognized standards are as follows:

1. National Electrical Manufacturers Association (NEMA) standards, which specify mounting dimensions for induction motors, allowing ready interchangeability of different makes of motors.
2. American Institute of Electrical Engineers (AIEE) standards, which specify the temperature limits of insulation materials and prescribe methods of rating and testing apparatus.
3. National Electric (NE) code, which is the general guide of city and insurance company inspectors in determining the type of enclosures and protection and installation of motors.
4. State laws, which are directed to increased safety to life and property and reduction of fire hazards.
5. City ordinances, which may include additional required precautions for prevention of human injury or fire damage.

The products of recognized manufacturers incorporate features which satisfy these requirements, and these products may be selected for each application.

TYPES OF ALTERNATING-CURRENT MOTORS

Alternating-current motors may be classified generally as either induction or synchronous types.

Induction Motors. Induction motors, both single-phase and polyphase, are simple in design, sturdy in construction, and require minimum care from the standpoint of operation and maintenance. They can be started by being thrown directly across the line, or by being accelerated automatically with magnetic control devices, without undue precaution as to sequence of operation by the attendant.

Induction motors operate at less than synchronous speed when loaded, the amount of lag or slip varying with the load. The power factor of induction motors is always less than unity and is lagging due to the lagging reactive component of magnetizing current.

All types of induction motors are based upon the principle that a rotating field is set up in the stator which in turn induces currents in the rotor winding. The reaction between the rotor winding and the revolving field causes the rotor to revolve.

Squirrel-Cage Induction Motor. The simplest form of induction motor is the "squirrel-cage" type, so called because its armature or rotating element, with bars short-circuited at their ends by heavy copper end rings, resembles a squirrel cage. See Fig. 15. The squirrel-cage principle is used in both single-phase and polyphase motors. The stator windings are distributed in the same manner as those of an alternator. The line leads are connected directly to the terminals of the stator, and there are no external connections to the short-circuited rotor winding.

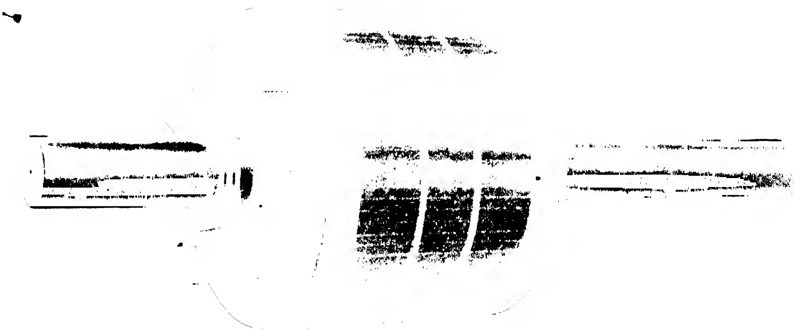


Fig. 15. Showing End Construction of Squirrel-Cage Rotor

Synchronous Motors. Synchronous motors, built commercially only for polyphase circuits, resemble revolving field alternators and, in fact, can be operated as alternators when connected to a driving unit of proper speed. Modern, general-purpose synchronous motors are built to operate under conditions of starting and running torque comparable to those named for induction motors and are about as simple in operation. Their somewhat higher price is not warranted in the smaller sizes, but they are available in horsepower capacities, speeds, and voltages paralleling induction motors above 20 horsepower.

Synchronous motors operate at synchronous speed and at unity power factor, or with leading power factor to compensate for the lagging power factor of inductive devices.

The development of starting equipment, both semimagnetic and magnetic, using automatic field application devices, has made the

synchronous motor practically as easy to operate as the simpler induction motor.

Single-Phase Motors. Because the squirrel-cage, polyphase motor is simpler in mechanical design and superior in operating characteristics to any design of single-phase motor, it is recommended wherever it is possible to obtain economically a three-phase service. However, it is recognized that in many locations, such as in rural and residential sections and in isolated parts of plants and buildings, it is impractical to install a three-phase power circuit for one or a few small motors.

Any Y-connected, three-phase induction motor, when connected with two of its line leads to a single-phase power source, will operate

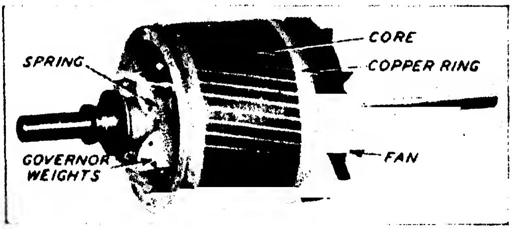


Fig. 16. Squirrel-Cage Rotor for High-Resistance, Split-Phase Motor

as a single-phase induction motor once it is brought up to speed. But such a motor has no starting torque because the course of the moving field produced by the stator winding is, at standstill, more nearly a straight line than a circular one. Therefore, it has no starting torque and will not start unless some means is introduced to cause phase displacement between the fields sufficient to produce an elliptical revolving field. The several principles employed to accomplish this end make the development of the single-phase motor to its present standard of performance an interesting study.

Split-Phase, Single-Phase Motors. The split-phase motor is built with a single-phase stator winding plus an auxiliary winding in space quadrature (90 degrees out of phase) with the main winding. This auxiliary winding is similar to the use of the third phase of a Y-connected three-phase winding where the third phase is 120 degrees out of phase with the main winding. The rotor is of the squirrel-cage type.

In the early motors of this type, the supply current was divided before it reached the motor. One branch passed through a reactance to the main winding, and the other passed through a noninductive resistance to the auxiliary or starting winding. When current was applied to this connection, the motor came up to speed after which the starting winding and the line reactance were cut out of the circuit by an external manually operated starting box.

In modern practice, the split-phase motor is built only in small sizes up to 1/4 horsepower, for applications whose torque and duty

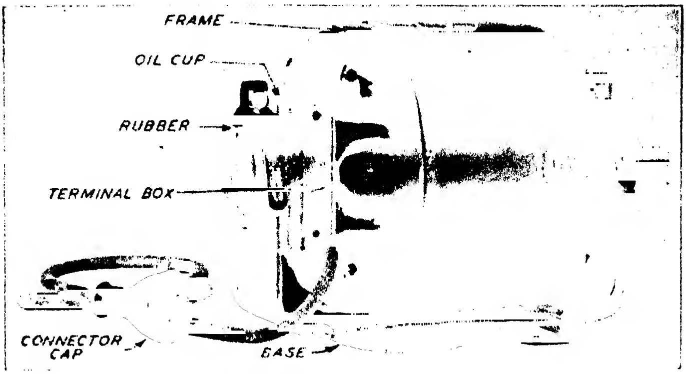


Fig. 17. Split-Phase Motor with Rubber Cushion Base

requirements are not severe. In these motors, the reactance is omitted; the extra resistance is produced in the starting winding itself by the use of high-resistance wire. The starting winding is cut out of the circuit by a centrifugally operated switch when the motor has come up to speed. See Figs. 16 and 17. Required control equipment is very simple and need be no more than a one- or two-pole switch to disconnect the two line terminals from the power source.

Split-phase motors are essentially constant speed. For very special low-torque applications, such as variable speed propeller fans, the variable speed is secured by inserting steps of resistance in series with the line. This practice is not recommended without special care in application, because operation below the speed at which the centrifugal switch is actuated will burn out the starting winding.

Repulsion-Induction Single-Phase Motors. The repulsion-induc-

tion motor is a self-contained unit capable of starting heavy loads and maintaining reasonably constant speed under varying load conditions.

The characteristics of the direct-current series-wound motor are well known. Operating through a wide range of speed and torque, this type has, however, no inherent speed regulation and its use is consequently confined either to fixed loads, like fans or pressure blowers, or to varying loads where the motor-controlling device is constantly under the operator's guidance. The speed, torque, and load characteristics of the series-commutator-type alternating-cur-

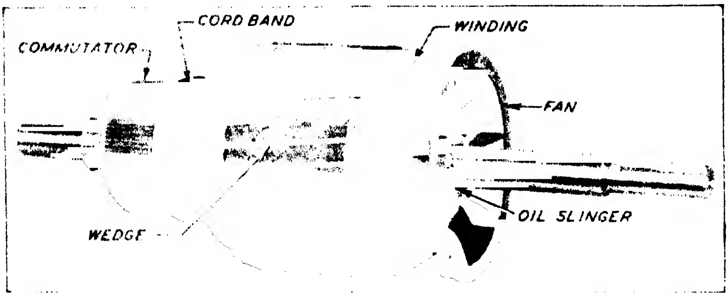


Fig. 18. Rotor for 3 Hp., 1,800 R.p.m. Repulsion-Induction Motor

rent motor being distinctly analogous to that of its direct-current prototype, the design fails to meet the requirements of constant-speed power service, this service demanding a motor which maintains good regulation after having once been brought up to speed, with torque values increasing as speed decreases; in other words, characteristics approaching those of the direct-current compound motor having the usual proportion of series-field winding.

The repulsion-induction motor, however, gives this combination of series and shunt characteristics; that is, a limited speed and an increased torque with decrease in speed. In the straight repulsion motor, to secure the necessary starting torque, a direct-current armature is placed in a magnetic field excited by an alternating current and short-circuited through brushes set with a predetermined angular relation to the stator. To further improve the operating characteristics of the plain repulsion motor, a second set of brushes (i.e., the compensating brushes) is placed at 90 electrical degrees from the main short-circuiting brushes (i.e., the energy brushes). The compensating field is auxiliary to the main field and impresses upon the

armature an electromotive force in angular and time phase with the electromotive force generated by the main field. In addition to correcting phase relation between the current and the voltage, thus giving approximately unity power factor at full load and power factors closely approaching unity over a wide range of load, the compensating field serves to restrict the maximum no-load speed and also permits, where varying speed service is involved, slight increase

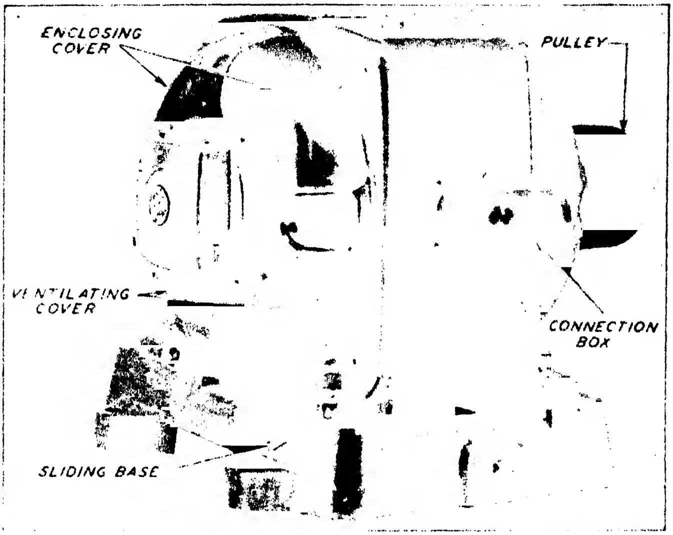


Fig. 19. Repulsion-Induction Motor (1 Hp.) with Sliding Base

over synchronous values. The compensated repulsion motor is practically an induction motor capable of operation either above or below synchronous speed, possessing high starting torque and high power factor at all loads as well as excellent efficiency constants. The motor has no tendency to spark or flash over, since the armature coils, successively short-circuited by the energy brushes, are not inductively placed in the magnetic field and consequently have only to commutate a low generated voltage. See Figs. 18 and 19.

Repulsion-induction motors may be started by throwing directly across the line. Starting rheostats are available for use where it is desired to reduce starting current to minimum.

These motors are sold in several types: constant-speed; constant-speed reversible; brush-shifting, adjustable varying speed (with series

characteristics), and adjustable varying speed, reversible. The adjustable varying speed types are applicable to the same type of loads as series direct-current motors. They provide 3:1 range of speed adjustment by the simple expedient of shifting brushes.

Capacitor Type Single-Phase Motors. The capacitor motor, employing a capacitor (static condenser) in the auxiliary winding

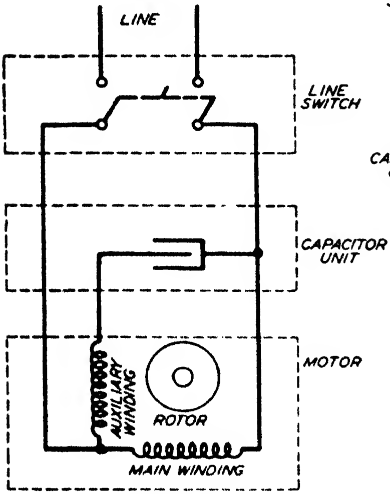


Fig. 20 Connection Diagram for Low-Torque Capacitor-Fan-Motor

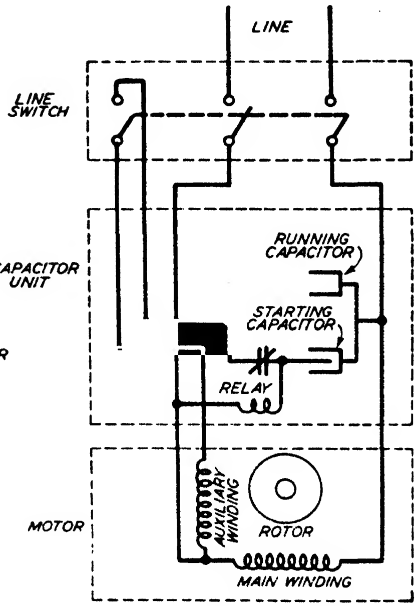


Fig. 21 Connection Diagram for High-Torque Capacitor Motor

circuit, is a recent development which is proving to be very popular. The principle of operation is identical to that of the split-phase motor, except that capacitance and inherent resistance instead of reactance and resistance are combined to produce the out-of-phase component of current with consequent starting torque.

The stator is wound with a main winding and an auxiliary winding spaced 90 electrical degrees out of phase. The rotor is of the squirrel-cage type, with the bars and end connections usually of aluminum, cast integrally.

Capacitor motors are of two types: low-torque, for fan duty, and high-torque for general-purpose applications. Fig. 20 shows the

connections of a low-torque motor with the capacitor permanently in the circuit—hence the term, capacitor start and run. In some motors the capacitor is in circuit only during starting. Such motors are

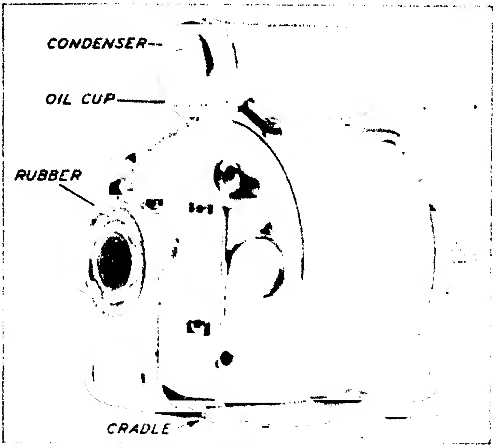


Fig. 22. Small Capacitor Start Induction Motor with Motor-Mounted Capacitor and Resilient Base

termed capacitor-start induction-run. In all sizes, the capacitor is mounted externally—on top of the motor in sizes up to approximately ½ horsepower, and separately, on wall or floor, in sizes up to 10.

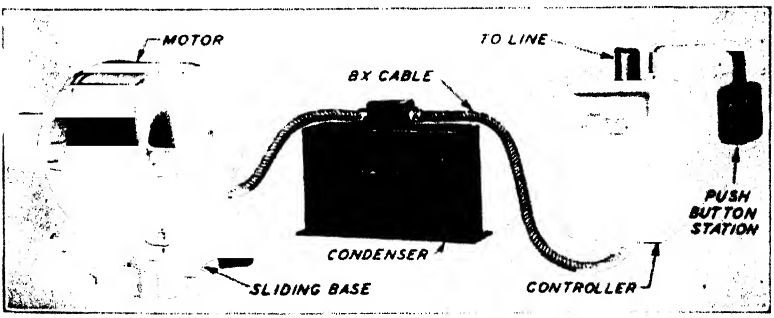


Fig. 23. High-Torque Capacitor Motor (5 Hp.) with Separately Mounted Capacitor Unit and Control

High-torque capacitor motors employ two condensers, one continuously rated for running, and the other intermittently rated for starting. A relay, mounted in the capacitor box, disconnects the starting condenser automatically when the motor has accelerated.

Fig. 21 shows connection of the high-torque type, and illustrates the need of a three-pole switch. Capacitor motors possess all the desirable characteristics of high power factor, high efficiency, permissible starting current for across-the-line starting, and quiet operation because of absence of centrifugal devices and commutator.

Figs. 22 and 23 illustrate two types of capacitor motors.

High- and low-torque fan motors may be furnished with adjustable varying speed control, allowing speed reduction of approximately 35 per cent. Such control is not applicable to high-torque, general-purpose motors, but the recent development of two-winding, multi-speed capacitor motors opens up that field to this type of motor.

POLYPHASE INDUCTION MOTORS

All types of polyphase motors described here are available for two-phase as well as three-phase circuits, with the exception of the two-speed, reconnected-winding type.

SQUIRREL-CAGE TYPES

The squirrel-cage induction motor is the simplest type of motor available and greatly outnumbers all other types in use. Fig. 24 is typical.

Constant-Speed Squirrel-Cage Motors. The constant-speed motor with single stator winding can be altered as to operating characteristics by changing the design of the rotor. In this manner, torque and starting current characteristics are produced to meet various operating conditions imposed by different loads and power company limitations. These characteristics are summarized as follows:

A. Normal torque, normal starting current—for general application, and generally requiring reduced-voltage starting equipment above 5 horsepower. Has low slip for close speed regulation.

B. Normal torque, low starting current—for general application; designed to meet most power company requirements as to starting current for motors up to and including 30 horsepower, to be thrown across the line. Has low slip for close speed regulation.

C. High torque, low starting current—designed to accelerate heavy starting loads at infrequent intervals. High-resistance rotor required to produce torque characteristic also produces the desirable low starting current. Has low slip for close speed regulation.

D. High torque, high slip—designed to accelerate heavy loads without shock. This type of motor is especially desirable for use with flywheels, because its

high-slip characteristic allows variation in speed without objectionable current pulsations to line and without undue heating of motor, if load peaks occur less than 25 times per minute.

All of the above types of motors have relatively high efficiency and power factor, although the high-slip motor sacrifices some efficiency. Table II, following, indicates average values for motors of the types described above, in ratings 7½ to 20 horsepower, 1,800 r.p.m., 60 cycles:

TABLE II

Efficiency and Power Factor for Squirrel-Cage Induction Motors

Type of Motor	Starting Torque	Maximum Torque	Per Cent Slip	Starting Current Across-the-Lane*	Efficiency*	Power Factor*
A	190	250	3	650	85	89
B	190	220	3	500	86	86
C	240	240	3.5	500	84	84
D	275	280	9	550	82	88

*Per cent of full load.

Values of starting and maximum torque are in percentage of full-load synchronous torque (T), derived from the following formulas:

$$T = \frac{hp. \times 5250}{r.p.m.} \tag{2}$$

where T = torque in pounds at one-foot radius

$hp.$ = horsepower rating of motor

$r.p.m.$ = synchronous speed in revolutions per minute

$$Slip\ in\ per\ cent\ (at\ full\ load) = \frac{Syn.\ speed - full\text{-}load\ speed}{Synchronous\ speed} \tag{3}$$

$$Full\text{-}load\ current = \frac{Horsepower \times 746}{Line\ voltage \times \sqrt{3} \times Efficiency \times Power\ Factor} \tag{4}$$

Efficiency and power factor at full load, expressed as decimals.

Multispeed Squirrel-Cage Motors. Multispeed motors are a modification of constant-speed, single-winding motors, with squirrel-cage rotors, and are of the following types:

1. Reconnectible-winding, two-speed motors, in which a single stator winding is reconnected in two different polar groupings, one connection always having one-half the number of poles of its complement. For instance, 4/8 poles to give 1,800/900 r.p.m., 6/12 poles to give 1,200/600 r.p.m., or 8/16 poles to give 900/450 r.p.m.—all at 60 cycles. Reconnectible-winding motors are available with two speeds for variable-torque, constant-torque, and constant-horsepower

applications. This type of motor is not available for operation on two-phase systems because of the difficulty of regrouping the coils of a two-phase winding to obtain different polar connections.

2. Two-winding, two-speed motors are built with two separate stator windings in the same slots and are, therefore, essentially two separate motors in the same frame, using the same squirrel-cage rotor. This type is adaptable to two-phase as well as three-phase circuits and is available for variable-torque, constant-torque, and constant-horsepower applications. The two speeds need not be limited to ratios of two to one, as for reconnectible motors, but are necessarily

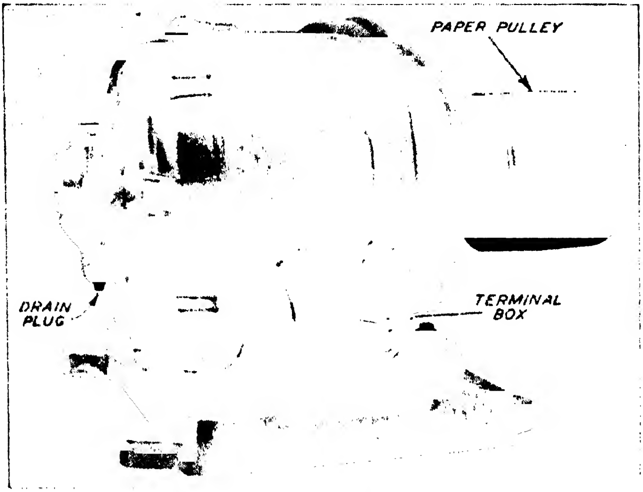


Fig. 24. Low-Voltage Polyphase, Squirrel-Cage Induction Motor with Sliding Base (20 Hp., 1,200 R.p.m.)

limited in range for constant-torque and constant-horsepower types because of limitation of output in each frame size. Variable-torque designs allow wide selection of speeds in the range 1,800/1,200/900/720/600/450 r.p.m. with 1,800, 1,200, 900, and 720 r.p.m. being the top speeds for any combination of speeds.

3. Three- and four-speed two-winding motors. A further combination of two separate windings, each of which is reconnectible in polar groupings, allows the derivation of three or four speeds from one motor. This type is limited to three-phase circuits for the reason given in paragraph 1 above. For example, one winding reconnectible from 4 to 8 poles, and another from 6 to 12 poles gives a motor rated 4/6/8/12 poles or 1,800/1,200/900/600 r.p.m. at 60 cycles. Another combination available is 6/8/12/16 poles giving 1,200/900/600/450 r.p.m., also at 60 cycles. A combination such as 1,200/900/720/600 r.p.m. would require a special three-winding motor. Three- and four-speed motors are also available with variable-torque, constant-torque, or constant-horsepower characteristics.

Multispeed motors were developed for applications requiring operation at one or more definite speeds below top speed, at relatively

high efficiency and at comparatively low first cost. They meet these requirements wherever adjustable-varying speed with a larger number of control points is not required.

Multispeed motors are designed with several starting-current and torque characteristics. Controlling devices for these motors are necessarily more costly than for single-speed motors, but are relatively simple.

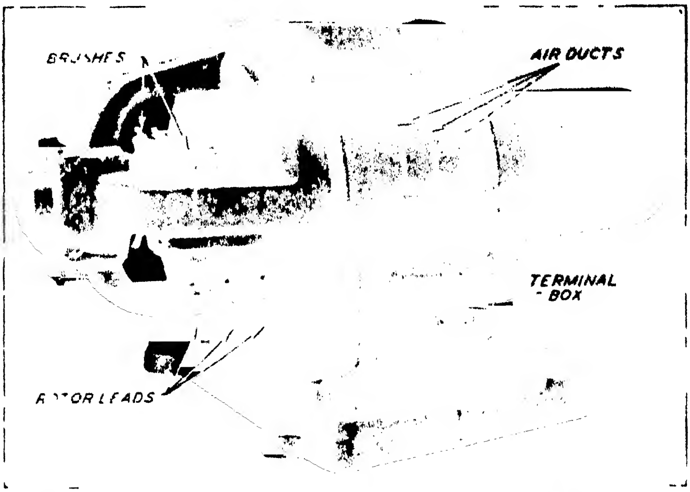


Fig. 25. Open Type Wound Rotor Induction Motor (40 Hp., 900 R.p.m.)

WOUND-ROTOR TYPE

In the wound-rotor type of induction motor, the stator (or primary) is wound exactly as in the squirrel-cage type, but the rotor (or secondary) is polar-wound, with the ends of the Y-connected rotor windings brought out to three collector rings mounted upon and insulated from the shaft. Thus, this type is frequently called a "slip-ring" motor. See Fig. 25. Brushes mounted in stationary brush holders complete the circuit to an externally mounted Y-connected secondary resistance.

The wound rotor, with external connections to slip-rings, allows the use of several layouts of external resistance to produce the desired torque during starting, or at reduced speed on speed-regulating points. This type of motor is applicable on loads requiring heavy

accelerating effort, and in locations where the starting current must be kept at a low value. The slip-ring motor offers the highest possible starting torque per ampere, full-load current producing approximately full-load torque at starting.

Control for simple starting duty is furnished with intermittent-rated starting duty resistor of such resistance value that approximately 250 per cent starting torque is produced with only 300 per cent starting current. Both values may be reduced, where required, by changing the resistance.

Slip-ring motor control for adjustable varying speed is designed with a continuous-duty resistor which allows the motor to be run continuously on any of its reduced speed points with a part of its resistor in series with the rotor windings. The secondary resistance layout, adjustable for varying speed control, must be differently designed for different types of load, such as variable torque—fan duty, and constant torque—machine duty. Therefore, these details must be furnished to the manufacturer.

Accurate speed control cannot be obtained below 50 per cent speed reduction, that is, two-to-one speed range, because of the proportions of secondary and external resistance values. Beyond that range, the speed change due to slight change of load torque becomes disproportionate.

Although the slip-ring motor with proper accessories allows varying speed control at relatively low first cost, its operation at reduced speeds is at the expense of efficiency. The electrical energy dissipated in the external secondary resistance must be added to the normal motor losses in determining overall efficiency. Operation at 50 per cent speed on a constant-torque load will be at approximately 50 per cent overall efficiency. For this reason, it is desirable to select, if possible, definite speeds at which the drive may operate, and use a suitable multispeed motor. If adjustable varying speed over a wide range is required, and if the motor must operate at reduced speeds a large part of the time, the brush-shifting motor may be the most economical, even at a higher first cost.

Brush-shifting Adjustable-Speed Motors. The brush-shifting adjustable-speed motor is a self-contained, reliable driving unit for operation on polyphase alternating-current circuits. These motors are built in sizes from 2 to 50 horsepower for three-to-one and four-to-

one speed range for constant-torque applications, and have shunt characteristics under these conditions. Motor speed is controlled by shifting the brushes, thus providing an infinite number of speed points within the speed range. Fig. 26 shows the connections of this type of motor.

The stator has one winding (the secondary), which is constructed like the stator (primary) winding of an induction motor, except that phases are electrically independent and both ends of each phase are

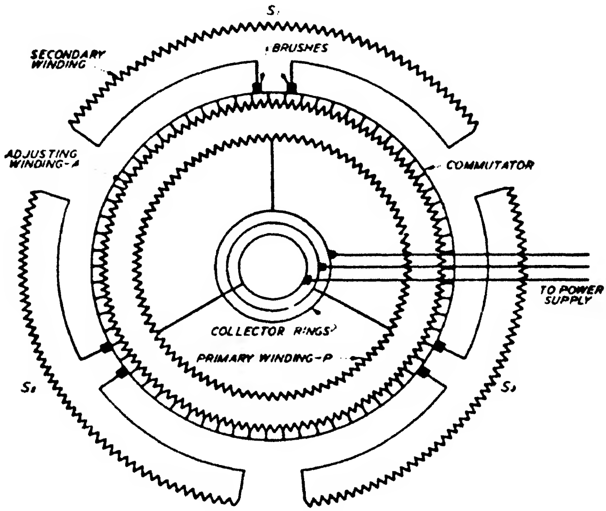


Fig. 26. Connections of Brush-shifting Adjustable-Speed Motor

brought out for connection to the commutator brushes. The rotor is provided with two windings placed in the same slots. The inner winding (primary) is identical in construction with the stator (primary) winding of a normal induction motor and is connected to the collector rings, to which the power is applied. The outer, or adjusting, winding is connected to the commutator in the same manner as in a direct-current motor.

Thus, the brush-shifting motor may be compared with the wound-rotor induction motor, having its primary winding in the rotor and its secondary on the stator. In addition, this machine has an adjusting winding in the rotor similar to a direct-current armature winding and connected to a commutator. The motor is provided

with two brush-holder yokes arranged to shift in such a way as to vary the voltage on the secondary winding.

One end of each phase of the stator (secondary) winding is connected to brushes on one brush yoke and the opposite end of each phase is connected to brushes on the other yoke. When the brushes, to which each end of a secondary phase is connected, are on corresponding commutator segments, the adjusting winding is, in effect, idle, the secondary winding is short-circuited, and the motor runs as an induction motor, with speed corresponding to the number of poles and frequency of supply. As the brushes are moved apart, a section of the adjusting winding is included in series with the secondary winding, causing the secondary winding to generate a voltage impressed upon it by the adjusting winding, thereby causing the motor to change its speed. Moving the brushes in one direction raises the speed, and moving them in the other direction reduces the speed. The motor operates both above and below the synchronous speed.

The motor is started on full voltage with the brushes in the low-speed position, as standard procedure. In this position, starting current is 125 per cent to 175 per cent of the full-load current at maximum speed. In most ratings, motors develop 200 per cent starting torque with less than 175 per cent starting current; in the larger sizes, starting torque is approximately 160 per cent, with less than 160 per cent starting current.

Where operating conditions require, it is possible to start the motor with the brushes in any position. In such cases, proper secondary resistance should be supplied to limit excessive current at starting. With such resistance, starting torque at the higher speed brush positions will be at least 250 per cent of normal full-load torque.

In the low-speed brush position, maximum running torque varies from 200 per cent of normal full-load torque on the smallest size to 160 per cent on the largest size. In the high-speed position, the maximum torque is at least 250 per cent of normal full-load torque on all sizes.

The efficiency of brush-shifting motors remains nearly constant over the greater part of their speed range, but it is somewhat lower at low speed. The average efficiency is high as compared with that of wound-rotor induction motors with secondary resistance, or as compared with direct-current motors and the apparatus necessary to convert alternating current to direct current.

Power factor is high when the motor is running at high speed, and even at synchronous speed the power factor is approximately the same as that of an induction motor of similar rating.

With full-load speed, approximately 1650/550 r.p.m. for a three-to-one ratio motor, the no-load speeds will be as follows: with the brushes in the maximum-speed position, 5 to 11 per cent higher than the rated full-load speed; with the brushes in the minimum-speed position, 17 to 43 per cent higher than the rated minimum speed.

These motors will operate continuously in either direction, provided the brush mechanism is set for the desired rotation. They may

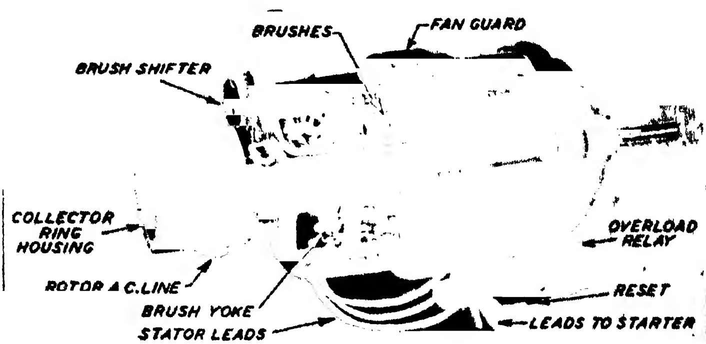


Fig 27 Brush-Shifting Adjustable-Speed Motor

be reversed by interchanging two line leads, as on an induction motor. Reverse operation should be allowed for short periods of time only, as the motor characteristics are impaired unless the brush-shifting mechanism is reset according to the instructions furnished with each motor.

Any creeping speed down to 50 per cent of the minimum rated speed may be obtained at rated torque for half-hour operation by means of secondary control. Overload or stalling protection is not provided when the motor is operated under these conditions.

Brush-shifting motors should be connected to the source of power in the same manner as any three-phase induction motor—by connecting the motor to the three lines. A magnetic switch, operated by a push-button station in conjunction with a temperature overload relay, mounted on the stator frame and connected in the stator circuit, provides low-voltage and overload protection at all operating

speeds. Slow-down or creeping speeds may be obtained by adding resistance in series with the secondary circuit and providing a switch for short-circuiting this resistance for normal operation.

Changes in speed by brush shifting are obtained in one of the three following ways:

1. Shifting the brushes by means of a handwheel or handle mounted on the motor. Fig. 27 shows a typical motor with motor-mounted handwheel.

2. Shifting the brushes by means of a handwheel or handle on a remote brush-shifting mechanism, which is mounted at a location convenient to the operator and connected to the motor by a chain.

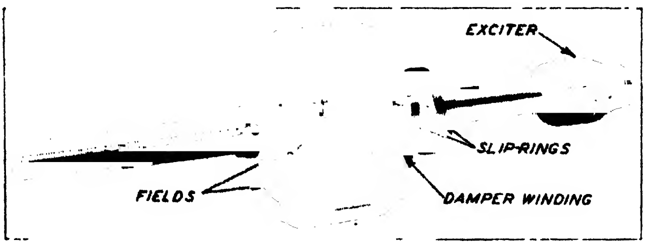


Fig. 28. Rotor for 75 Hp 1 200 R p m Synchronous Motor with Direct-Connected Exciter

3. Shifting the brushes by means of a pilot motor and reduction-gear mechanism, which is mounted on the motor and controlled by push buttons located elsewhere.

Miscellaneous Polyphase Motors and Variable-Speed Systems. For description of the Noel Capacitor motor and Fynn-Weichsel variable-speed motors, see Power-Factor Correction.

Heavy-duty adjustable varying speed drives are available in the Krämer and Scherbius systems of speed control. Both employ a slip-ring motor as the main driving unit and use accessory equipment to derive changing excitation and power for range of speed required. Additional details concerning these systems may be obtained from manufacturers of electric equipment.

SYNCHRONOUS MOTORS

Synchronous motors, as the name implies, operate at synchronous speed—that is, with no slip. They are practically identical in construction with (synchronous) alternators or generators, having a

three-phase wound stator and a rotating field consisting of direct-current excited coils of alternately opposite polarity, connected in series to a direct-current excitation source at its slip rings. Modern practice is to use 125-volt direct-connected exciters for each motor unit, particularly at the higher speeds. At low speeds, it is sometimes economical to supply excitation, either 125 or 250 volt, to one or more motors from a high-speed motor-driven exciter set. (Generally with additional stand-by set.) To provide uniform and sufficient starting

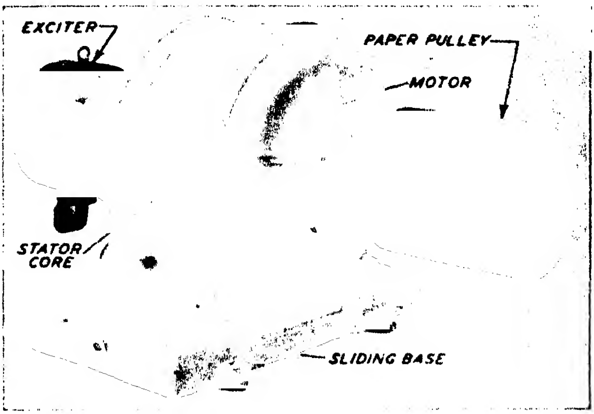


Fig. 29. Synchronous Motor and Base for Pulley Drive (50 Hp., 80 Per Cent Power Factor, 1,200 R.p.m.)

torque for general use, synchronous motor rotors are built with starting windings imbedded into the faces of the field pole pieces and short-circuited at their ends by circular rings. These are similar to the squirrel-cage winding of an induction motor. See Fig. 28.

Synchronous motors operate with minimum excitation at unity power factor—that is, when the line current drawn by the motor is exactly in phase with the voltage. Unity power-factor motors are widely used to raise the average power factor of a plant employing a large number of smaller induction-type motors operating at lagging power factor, that is, with line current lagging behind voltage by an angle whose cosine equals the power factor expressed as a decimal.

When increased excitation is applied to the field of a synchronous motor, we have what is known as a leading power-factor motor capable of supplying leading reactive kva to a system to compensate for

lagging reactive kva drawn by induction machines. Such motors are generally rated in horsepower at .80 leading power factor. The power factor corrective feature of synchronous motors will be discussed in more detail under Power-Factor Correction.

Unity power factor and .80 power factor general-purpose synchronous motors are available in all ratings from 20 horsepower up. Designed with starting torque and pull-in torque of approximately 110 per cent of rated full-load torque, they can be applied to all normal duties except those requiring heavy starting torque and extremely high maximum or pull-out torque. See Figs. 29 and 30.

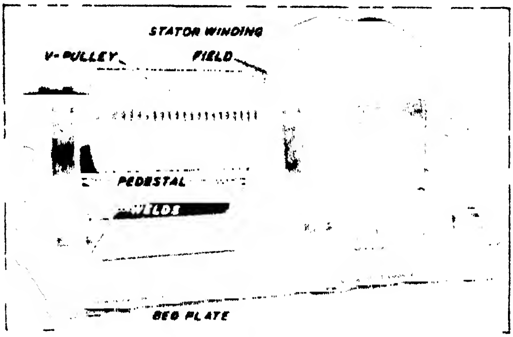


Fig. 30 Three-Phase 60-Cycle Synchronous Motor with Outboard Bearing and Sheave for V Belt Drive (300 Hp 80 Per Cent Power Factor 600 R p m 2,200-Volt)

Synchronous motors are best suited for loads requiring a nearly constant torque—that is, one without instantaneous pulsations. On a load producing pulsations in shaft torque, a synchronous motor will draw high current from the line at each pulsation because, being a synchronous machine, it will tend to pull out of step. Wherever synchronous motors are used to drive reciprocating compressors and similar machines, flywheel effect to absorb the pulsations must be provided in the rotor of either or both the motor and the compressor.

In general, since the major utility of synchronous motors is derived from their unity power-factor operation or their ability to supply leading reactive kva, their relatively higher cost (as compared with induction motors) cannot be justified except on practically continuously operated machines. Obviously, no power-factor correction can come from such a machine when it is not operating.

Synchronous motors can be started by throwing directly across the line, and, when so started, the current drawn by a high-speed motor is approximately that of a normal-torque, normal-starting-current motor—that is, 600 per cent. When started by reduced-voltage starting equipment, the starting current corresponding to full-load torque is from 350 to 400 per cent of full-load current. Low-speed motors seldom require reduced-voltage starting equipment because their average full-voltage starting current is only 300 per cent of full-load current.

Starting equipment for synchronous motors is available in semi-magnetic and full-magnetic forms, both for full-voltage and reduced-voltage starting. In all forms, the field is applied automatically. This feature eliminates much of the necessity for care previously required in the operation of synchronous motors.

ERECTING AND LINING UP ALTERNATING-CURRENT GENERATORS

The erecting and lining up of alternating-current generators and motors involve the same principles and procedures as for direct-current machines. The same general details regarding making of electrical connections of direct-current machines also apply for alternating-current machines.

Wiring Connections. Wiring connections for an alternating-current generator consist, essentially, of leads between generator stator terminals and line side of generator switch, and leads from load side of generator switch to bus. The excitation circuit is connected from source through field switch to generator field and includes a rheostat in series with the field circuit. See Fig. 31.

If the excitation source is a direct-connected exciter, the field rheostat may operate only on the exciter shunt field; or, on larger machines, there will be both an exciter field and a generator field rheostat operated by a concentric type switchboard mechanism. There will also be accessory voltmeters, frequency meter, ammeters, etc., depending on the refinements required in the controlling switchboard. For small generators under 100 kva and not to be operated in parallel with other units, the field switch is often omitted since there will be no occasion to "kill" the field.

Practically all generators, whether for single or for parallel operation, require generator-voltage regulators. These regulators act upon the exciter field to maintain constant generator terminal voltage. The voltage regulation of a standard alternating-current generator is approximately 30 per cent—that is, the voltage at constant excitation will drop 30 per cent from no load to full load. It is impractical to adjust the excitation manually for varying load.

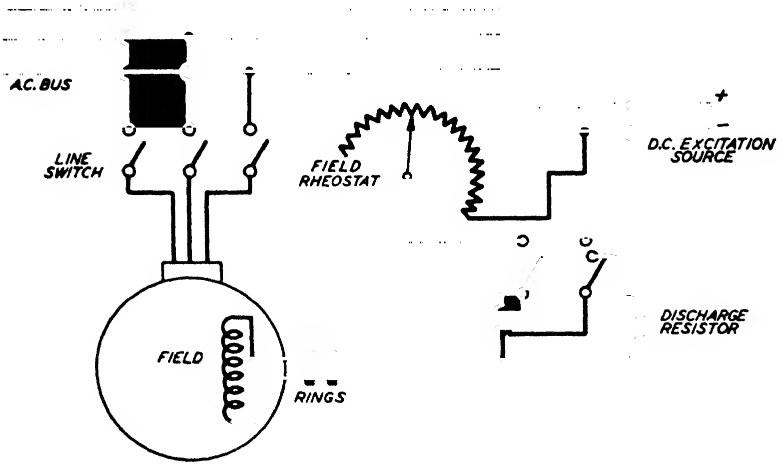


Fig. 31. Typical A-C Generator Wiring Diagram

Parallel Operation. Generators which are to be operated in parallel demand voltage regulators. To assure the maintenance of system stability, the combination of generator-voltage regulator and exciter characteristic should be as nearly identical as possible. Furthermore, the speed regulation characteristic of speed governing devices on prime movers must be carefully paralleled.

To run two alternators in parallel, several conditions have to be fulfilled: The incoming machine—as in the case of direct-current machines—must be brought up to nearly the same voltage as the first one; it must operate at exactly the same frequency; and, at the moment of switching in parallel, it must be in phase with the first machine. This correspondence of frequency and phase is called "synchronism."

Synchronizing Alternators by Lamp Indicaior. It is impossible with mechanical speed-measuring instruments to determine the

speed as accurately as is necessary for this purpose. There is, however, a very simple method of electrically determining small differences in speed or frequency. In Fig. 32, let M and N represent two single-phase alternators, which can be connected by means of the single-pole switch A—B. Across the terminals of the switch is connected an incandescent lamp L, capable of standing twice the voltage of either machine. When A—B is open, the circuit between the machines is completed through L. The two machines may be connected in parallel as follows: Assume machine M already in operation; bring up machine N to approximately the proper speed and voltage; then watch lamp L. If machine N is running a very little slower or faster

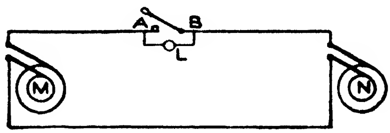


Fig. 32. Diagram of Two Single-Phase Alternators Arranged in Parallel

than machine M, the lamp L will glow for one moment and be dark the next. At the instant when the voltages are equal in pressure and phase, L will remain dark; but when the phases are displaced by half a period, the lamp will glow at its maximum brilliancy. Since the flickering of the lamp is dependent upon the difference in frequency, the machines should not be thrown in parallel while this flickering exists. The prime mover of the incoming machine must be brought to the proper speed; and the nearer machine N approaches synchronism, the slower the flickering. When it is very slow, and at the instant when the lamp is dark, throw the machine in parallel by closing the switch across A—B. The machines are then in phase, and tend to remain so, since if one slows down, the other will drive it as a motor. It is better to close the switch when the machines are approaching synchronism rather than when they are receding from it; that is, at the instant the lamp becomes dark.

Fig. 33 shows the method of synchronizing high-voltage alternators through step-down transformers. The first machine to be started becomes "bus" and succeeding machines are paralleled, "machine to bus." When two three-phase alternators are first placed

in operation, synchronizing connections should be made across each phase. If all the lamps become bright or dark simultaneously, the alternators are ready for parallel operation. After all phases have once been tested, it is only necessary to compare a corresponding phase from each machine to indicate synchronism.

The connections, as shown in Fig. 33, indicate synchronism when the lamps are dark. If it is desired that a condition of synchronism

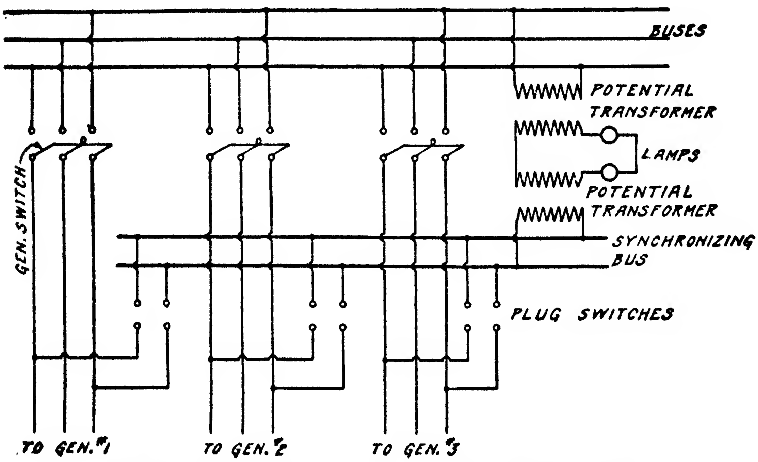


Fig. 33. Diagram of Connections for Synchronizing High-Voltage Alternators through Step-Down Transformers

shall be indicated when the lights are at maximum brightness, reverse the secondary connection of either one of the potential transformers.

Synchronizing Alternators by Means of a Synchroscope. The synchroscope affords the quickest and safest means for paralleling machines, since it shows when the machines are in step and in phase, indicating by the position of the needle the difference in the phase relations between the machines, and telling whether the incoming machine is running too fast or too slow. It is superior to synchronizing with lamps, because the latter give no indication of the relative speed of the incoming machine. The lamps will indicate when the machines are of the same frequency, but the phase relations can be judged only by the brilliancy of the light.

When synchronizing with lamps dark, the phase relations of the machines will be shown by the brilliancy of the light to a point where

the machines are approximately 45 degrees out of phase, below which point there will not be sufficient voltage across the lamp to make it glow. Again, in case there is an inopportune failure of the lamp, the operator might be misled and throw the machines together when out of phase, with possible disastrous results.

When synchronizing with lamps bright, it is difficult to determine, after watching the lamps for some time, at just what instant

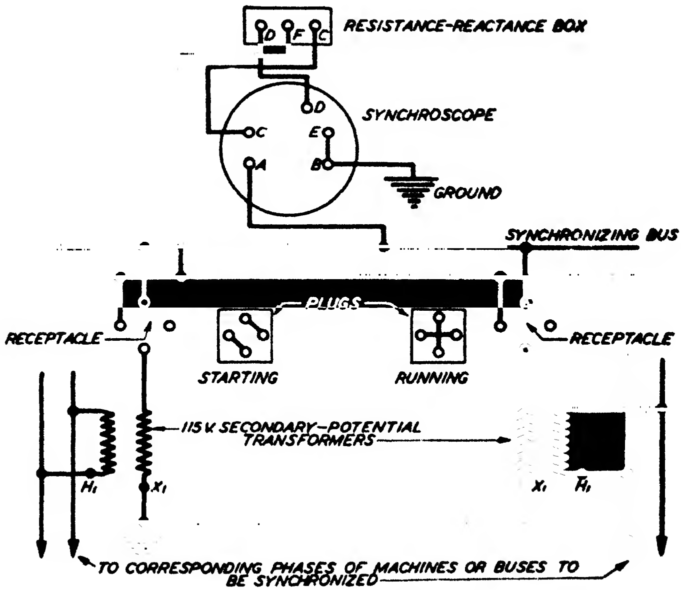


Fig. 34. Synchronizing by Use of Plugs and Synchroscope

they are burning at full brilliancy, and therefore, at just what instant the machines are in synchronism.

Fig. 34 shows a method of connecting a synchroscope to two machines (one running and one starting) by means of plugs and receptacles mounted on the switchboard. Either machine may be the "Starting" or "Running" unit. To insure safe operation, only one of each of the plugs marked "Starting" and "Running" should be available at any switchboard. H_1 and X_1 are polarity markings on the potential transformers.

Fig. 35 shows connections for using a synchroscope and synchronizing switches to accomplish the same method of synchronizing,

as shown in Fig. 34, with the added safeguard of oil circuit breaker interlocks, a feature which allows the closing of only the breaker of the machine being synchronized. As in the plug method, one each of "I" and "R" removable handles are furnished for each switchboard.

When two alternating-current generators have been connected in parallel, the division of load should be adjusted. This cannot be

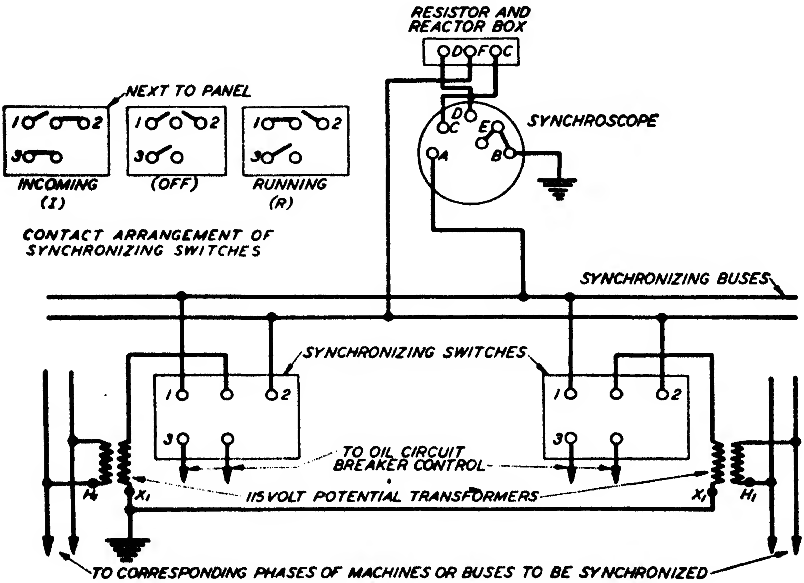


Fig. 35 Synchronizing with Synchroscope and Synchronizing Switches. Removable Handle *I* Effects Contact Arrangement "Incoming"; Removable Handle *R* Produces "Running"

accomplished as in direct-current machines by adjustment of the field rheostat. Change in field strength will cause more current to flow, but it will be 90 degrees out of phase with the voltage and will not represent actual power. The only way to make the two machines supply proportional amounts of power is to adjust the speed of their respective prime movers. The governors of engines driving alternators, operating in parallel, should be provided with a means whereby the speed can be adjusted within a small range without throttling and while running. Without this refinement, trouble will be encountered when trying to synchronize and adjust for proper division of load. If it is desired to make the machine carry more load, its prime

mover must be adjusted for an increase in speed, and conversely to make the machine carry less load.

If it is found necessary to increase the voltage of machines operating in parallel, the rheostats of all machines should be adjusted proportionally. If the rheostat of only one machine is shifted, cross currents will be caused to flow between the paralleled machines. These cross currents do not represent actual power but do cause undesirable heating of the machines.

OPERATION

Directions for Running Generators and Motors. *Preliminary Run with No Load.* If possible, a new machine should be run with no load or with a light one for several hours. It is bad practice to start a new machine with its full load or even a large fraction of it. This is true even if the machine has been fully tested by its manufacturer and is apparently in perfect condition, because there may be some fault produced in setting it up, or some other circumstance that would cause trouble.

All machinery requires some adjustment and care for a certain time to get it into smooth working order.

Voltage and Current Regulation. A generator requires that its voltage or current should be observed and regulated if it varies. The attendant should always be ready and sure to detect and overcome any trouble, such as sparking, heating, noise, abnormally high or low speed, etc., before any injury is caused. Such directions should be thoroughly committed to memory in order promptly to detect and remedy any trouble when it occurs suddenly, as is usually the case. If possible, the machine should be shut down instantly when any indication of trouble appears, in order to avoid injury and to give time for examination.

Keep Tools Away from Machines. Keep all tools or pieces of iron or steel away from the machine while running. Otherwise, they might be drawn in by the magnetism, perhaps getting between the armature and pole pieces, thus ruining the machine.

Commutator and Brushes. Particular care should be given to the commutator and brushes, so that the former is kept perfectly smooth and the latter are in proper adjustment. Avoid lifting brushes when machine is operating, unless there are several brushes in parallel.

Bearings. Touch the bearings occasionally to see whether or not they are hot. Thermometers embedded in putty will assist in detecting undue temperature rise.

Overloading. Special care should be observed by anyone who runs a generator or motor, to *avoid overloading* it, because this is the cause of most of the troubles which occur.

Personal Safety. The matter of personal safety is of great importance in the installation, care, and management of dynamo-electric machinery, both from the humanitarian and from the financial standpoint.

Precautions in Handling the Circuit. The safest rule is never to touch any conductor carrying current, and never to allow the body to form part of an electric circuit, no matter what the voltage. This, of course, is a rule which cannot be followed strictly in practice. However, every precaution should be taken to prevent accidents, and every device which adds to the personal safety of the men should be employed. Rubber gloves, rubber shoes, or both, should be used in handling circuits of 500 volts or over. Also these articles should be tested frequently. Tools with insulated handles, or a dry stick of wood, should be used instead of the hand for handling the wires. It should always be remembered that a wire may be "alive" through some unknown change in connection or through accidental contact with another wire, even when it is thought to be "dead."

High Voltages. On the high alternating-current voltages now so common, even the above precautions are not sufficient. No work can ever be done on such circuits unless they are entirely disconnected from all sources of power. In addition, the wires should be thoroughly grounded before being touched. In grounding, the ground connection should be first made and last disconnected.

Stopping Generators. *Operating Alone.* A generator operating alone on a circuit can be slowed down and stopped without touching the switches, brushes, etc., in which case the current gradually decreases to zero. Then the connections can be opened without sparking or any other difficulty.

Operating in Parallel. However, when a generator is operating in parallel with other sources of power, it must not be stopped until it is entirely disconnected from the system. Furthermore, the current generated by it should be reduced nearly to zero before its switch is

opened. For alternating-current generators, the load is reduced by adjusting the engine governor to reduce the input. The setting of a field rheostat should not be changed.

Never, except in an emergency, should any circuit be opened when heavily loaded; the flash at the contact points, the discharge of magnetism, and the mechanical shock are all decidedly objectionable and destructive.

Stopping Motors. Any alternating-current motor, whether operating singly or with several others on a feeder, may be stopped by simply throwing its manual starter to the "off" position, or by pressing the control "stop" button, if the control is of the magnetic type. No precaution is required before restarting except to be sure that all resistance is reinserted in the secondary of slip-ring motors, and that, in synchronous motors, the field switch is open.

POWER-FACTOR CORRECTION

Low power factor and its consequent evils apply only to alternating-current systems. Power factor may be simply defined as the cosine of the angle by which the current vector leads or lags behind the voltage vector of a given circuit. Although it seldom, if ever, exists, an excessive leading power factor would be as troublesome as a lagging power factor.

Induction motors, induction furnaces, series lighting transformers, and other inductive devices draw a magnetizing component of current which lags behind the line voltage and lowers the power factor of the system. The magnetizing current of an induction motor is nearly constant at all loads with constant voltage. This current lags 90 electrical degrees behind the impressed voltage and does no useful work.

Figs. 36 and 37 show the comparison of magnetizing current, power current, and resultant power factor on a fully loaded and lightly loaded motor. The magnetizing current, OX, being practically constant and the power current, OP, decreasing from full load to light load, the angle θ increases and the power factor decreases. OL, in both cases, represents the current drawn from the line. This illustrates the reason for lower power factor of induction motors at light loads and the necessity of applying motors at near rated capacity.

The effect of low system power factor is far-reaching, in that it increases the size of cables, switches, transformers, and even generators required to deliver a given amount of useful power current. It further affects the system stability by increasing the regulation—that is, impairing the stability of operation, of lines, transformers, and generators. Low power factor imposes an added current load upon all parts of a system with the result that power companies in some localities have rate schedules incorporating a power factor clause which adjusts the rate according to power factor. Other rate schedules allow a bonus if power factor is, for example, above 90 per cent; others

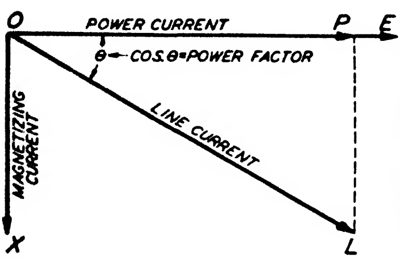


Fig. 36. Vector Diagram of a Squirrel-Cage Induction Motor Fully Loaded

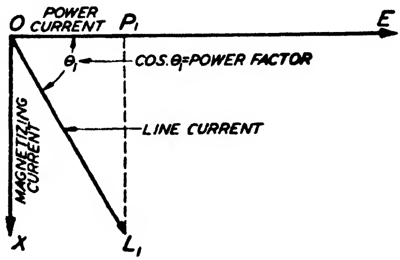


Fig. 37. Vector Diagram of a Squirrel-Cage Induction Motor Lightly Loaded

involve a penalty if below 80 per cent; still others specify a flat minimum allowable power factor.

Specific examples will best illustrate the effect of power factor upon line currents. For instance, let us consider a 50-hp., 1,800-r.p.m., 220-v, 60-cycle induction motor which has a full-load efficiency and power factor of .90 and .91 respectively. At full load, its line current will be $\frac{50 \times 746}{220 \times \sqrt{3} \times .90 \times .91} = 120$ amperes. A similarly rated unity (1.00) power factor synchronous motor with full-load efficiency of 91.4 per cent would draw a line current equal to $\frac{50 \times 746}{220 \times \sqrt{3} \times .914}$, or 107 amperes exclusive of exciter and rheostat losses.

This comparison, although using a fully loaded, high-efficiency, and relatively high power factor induction motor, illustrates a line current requirement 12 per cent higher for the induction motor than for the synchronous motor. Further, let us assume a 440-v, three-phase power circuit carrying a load of 500 kw at .80 power factor.

The resultant line current is $\frac{500{,}000}{440\times\sqrt{3}\times .8}=820$ amperes. If the power factor could be raised to unity (1.00) through the use of synchronous motors or other corrective equipment, the same line could carry $820\times 440\times\sqrt{3}=625$ kw—an increase of 25 per cent in power with the same line current. Conversely, if the power factor should remain at .80 as originally, the system would require 25 per cent more copper, transformers, and generating capacity to produce the same output (625 kw) as could be secured by installing power factor correction equipment.

A more severe condition of original system power factor and its improvement to .95 power factor is illustrated by the following chart,

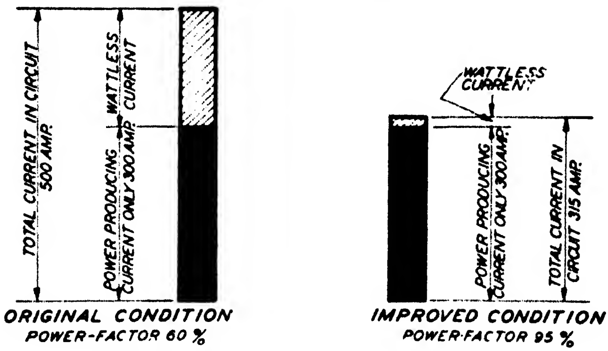


Fig. 38. Chart Showing Result of Adding Power-Factor Correction Apparatus

Fig. 38, which indicates reduced current demand from the power lines for a given amount of kw load at higher power factor.

Methods of Correcting Power Factor. Referring to Fig. 36 it is evident that if it is possible to counteract the lagging component of reactive current (magnetizing current) by introduction of a leading component of reactive current, the resultant angle θ between power current and line current will be diminished and cosine θ or power factor will be increased.

Fig. 39 illustrates the effect of adding leading reactive current to the system. A number of methods are available to accomplish this desired result, as follows:

1. Substitution of synchronous motors for existing induction motors.

2. Use of synchronous motors for additional load requirements.

3. Installation of synchronous condenser.

4. Use of power factor corrective motors, such as Noel capacitor motors and Fynn-Weichsel motors.

5. Installation of capacitors (static condensers).

Under *Methods One (1) and Two (2)*, the use of unity power-factor synchronous motors would increase the average power factor of the

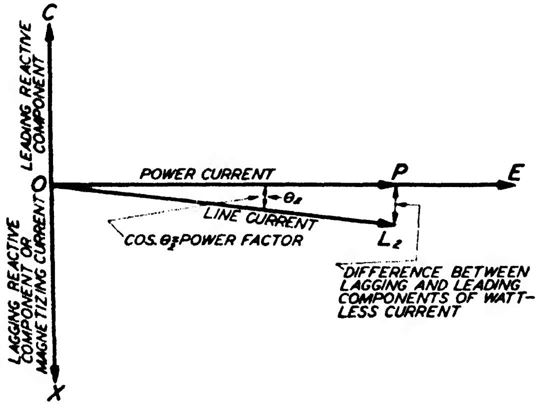


Fig. 39. Diagram Showing How a Leading Reactive Current Improves the Power Factor

system load without adding corrective leading kva. However, if leading power-factor motors are used, they will deliver to the system leading reactive kva equal to $\frac{.746 \times hp.\ rating}{Efficiency \times P\text{-}F}\sqrt{1 - P\text{-}F^2}$, in which power factor is expressed as a decimal.

Method Three (3). A synchronous condenser is simply a synchronous motor running on the line without shaft load and supplying leading current to the line. By varying the excitation the amount of leading kva can be changed at will. This system of correction is not used on low-voltage distribution systems ordinarily. It is more economical to use a synchronous motor partly loaded and excited to run at .70 to .80 leading power factor, enabling both a power load and wattless leading kva to be derived from the same unit.

Method Four (4). The Noel capacitor motor is a standard, squirrel-cage induction motor except that in the bottom of the stator slots there is placed a separate three-phase winding which is connected to a

three-phase capacitor. This capacitor winding is so designed that with 220 or 440 volts applied to the main winding, 600 volts is impressed upon the capacitor by transformer action with the capacitor winding. Therefore, this motor operates at near unity power factor.

The Fynn-Weichsel motor is a form of synchronous induction motor. The rotor is wound with two windings—one, the power winding, fed through slip rings, and the other, an exciting winding which delivers power to a commutator. The stator is also furnished with two windings—one functions similarly to a regular slip-ring motor secondary winding; the other receives the commutated current from

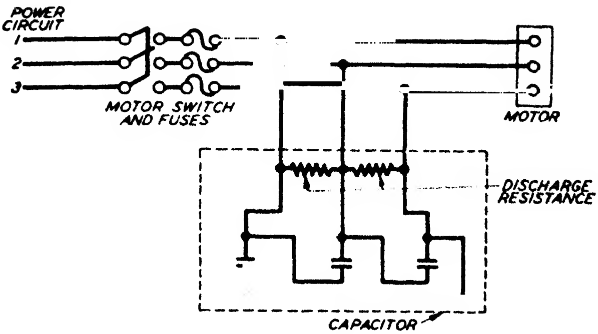


Fig. 40. Connection Diagram of Enclosed Capacitor Unit Installed at Motor Terminals

the commutator and excites the motor in much the same manner as do the poles of a synchronous motor. This motor starts similarly to a slip-ring induction motor, but assumes synchronous characteristics at full speed. This type of motor should be applied on a load which remains as nearly constant as possible and at near rated capacity since it is designed to give maximum power factor correction to rated load.

Method Five (5). Capacitors are adaptable for installation wherever it is desired to raise the power factor, at the individual motors (Fig. 40), at distribution points feeding a group of motors with relatively short feeders (Fig. 41), or at the main switchboard to improve the combined power factor of the entire distribution system (Fig. 41). They are available in small individually mounted units, or in larger rack-type equipments for operation on circuits from 230

volts to 6,900 volts, and in enclosures suitable for mounting indoors and out of doors. See Figs. 42, 43, and 44.

Capacitor Calculations. Let us assume that it is desired to calculate the size of capacitor necessary to improve the power factor

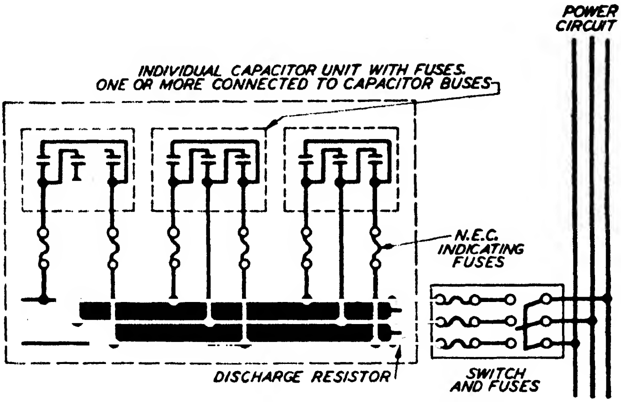
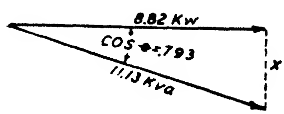


Fig. 41 Connection Diagram of Capacitor Installed in Power Circuit

of a 10-hp. 900-r.p.m. induction motor to unity. The full-load efficiency and power factor of this motor are 84.6 per cent and 79.3 per cent respectively. The kw input to the motor is $\frac{\text{hp.} \times .746}{\text{Efficiency}} = \frac{10 \times .746}{.846}$ $= 8.82$ kw. The kva input to the motor is $\frac{\text{kw input}}{\text{power factor}} = \frac{8.82}{.793} = 11.13$ kva. By the use of trigonometry, we can determine the value of reactive lagging kva, x, as follows:

$$x = \sqrt{11.13^2 - 8.82^2} = 6.8 \text{ kva.}$$



Therefore 6.8 kva of leading reactive kva must be supplied by a capacitor to neutralize the lagging component and produce unity power factor.

The size of capacitor required to raise the power factor of a given load to a higher value can be found easily, as in the following example:

Fig. 42. Three-Phase, 60-Cycle Enclosed Capacitor Unit (3-Kva., 230-Volt)

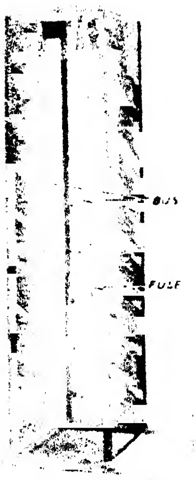


Fig. 43. Three-Phase, 60-Cycle Indoor Rack-Type Capacitor Unit (120-Kva. 460-Volt)

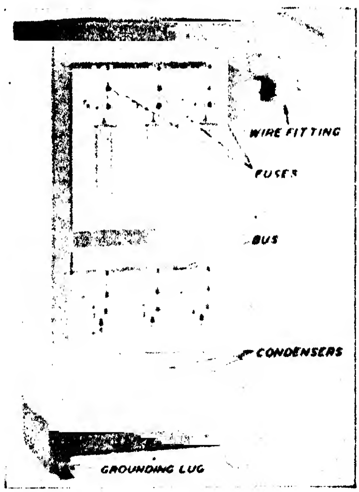


Fig. 44. Three-Phase, 60-Cycle Outdoor Capacitor Unit, Side Removed (60-Kva, 460-Volt)

Assume it is desired to raise the power factor of a 300-kw load from 60 per cent to 90 per cent.

A 300-kw load at 60 per cent power factor has an apparent load of $\frac{300}{.6}$ or 500 kva, and has a lagging component of $\sqrt{500^2-300^2}$, or 400 kva.

A 300-kw load at 90 per cent power factor has an apparent load of $\frac{300}{.9}$ or 333 kva, and has a lagging component of $\sqrt{333^2-300^2}$, or 145 kva.

The difference between the two lagging components (400 − 145) is 255 kva and is the leading kva that will be necessary to raise the power factor to 0.90.

Fig. 45. Curve Showing Capacitor Required to Give Desired Power-Factor Improvement

Determination of capacitor required to give desired correction in power factor. Follow horizontal line corresponding to present power factor of load until it intersects curve representing power factor desired. The vertical projection of this intersection on the base gives the size of capacitor required in per cent of kw. load.

Example. Load 300 kw. Present power factor 60 per cent, power factor desired 90 per cent. Projection of intersection of 60 per cent power factor line with 90 per cent power factor curve gives desired capacitor as 84.9 per cent of 300 kw., or 255 kva.

To simplify these calculations, factors by which the kw load can be multiplied to give the size of capacitor necessary can be taken directly from the curves in Fig. 45.

Each method of power factor correction has its field of application and it is possible that a combination of at least two types of corrective equipment can be selected for each plant or building. However, correction by capacitors appears to be the most acceptable method, for the following reasons:

1. They can be installed in any location without disturbing existing equipment.

2. Corrective capacity can be selected at will, with no dependence upon operating conditions, such as continuity of load.

3. Capacitors produce their corrective effect every moment they are connected to the line, and since they are static, i.e., have no moving parts, there is little likelihood of necessity for repairs.

STARTING AND CONTROLLING DEVICES FOR ALTERNATING-CURRENT MOTORS

Starters and controllers for alternating-current motors normally include all switches and contactors necessary for controlling the starting operation and speed regulation (where required) plus thermal overload devices to protect the motor against normal overload. All parts are of adequate capacity to break the normal overload or stalled current of the motors to which they are connected, but are not designed to interrupt short-circuit currents which may be caused by grounded or short-circuited wires and cables. Circuit-interrupting devices such as fuses, air circuit breakers, or oil circuit breakers of adequate interrupting capacity should be installed ahead of the control equipment to protect feeder lines and control, and also to meet Underwriters' and Code requirements.

All circuit diagrams shown hereafter in this section are standard, as used by the General Electric Co., and are shown to be illustrative of general types. All diagrams are used by courtesy of the General Electric Co.

Single-Phase Motor Starters. Single-phase motors may be started and adequately protected against overload by manual or magnetic two-pole switches, with one overload coil. The only exception is in the case of the high-torque capacitor motor which requires a third pole to disconnect the running capacitor.

Polyphase Motor Starters and Controllers. *Squirrel-Cage Induction Motors.* For small sizes, manually operated starters with two-coil overload protection are available. These do not provide undervoltage protection or facility for remote control by push-button, or pilot control such as float switch and pressure switch. Fig. 46 illustrates connection of a magnetic across-the-line starter for constant-speed motors.

Fig. 47 shows the circuit of a magnetic reversing switch for squirrel-cage motors.

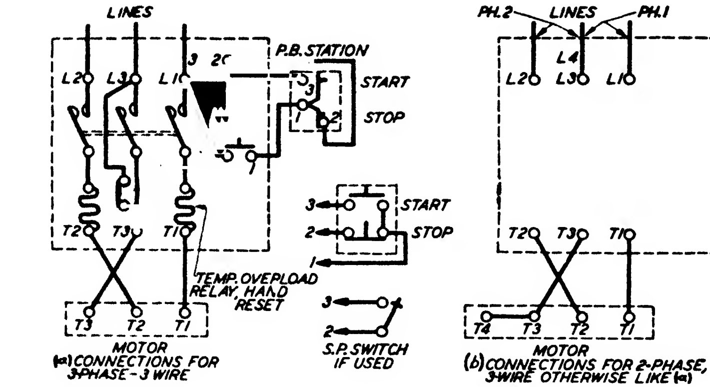


Fig. 46. Connection Diagram for Across-the-Line Magnetic Starter

Pressing the push button marked *Start* allows current to flow from line *L1* to contacts *3* and *2*, through the contactor coil and the temperature overload relay contacts to line *L3*. This causes the contactor to close, connecting the motor terminals *T1*, *T2*, and *T3* directly to the line wires *L1*, *L2*, and *L3* respectively.

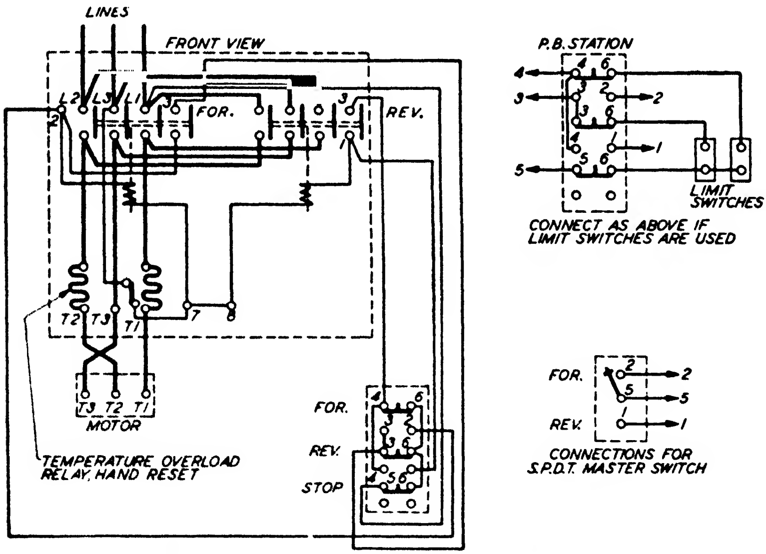


Fig. 47. Connection Diagram for Reversing Magnetic Controller

Pressing the *For.* button allows current to flow from line *L1* to *Stop* and *Rev.* buttons, contacts *3* and *2*, terminal *2* near the forward contactor, through the *For.* contactor coil, terminal *7*, temperature overload relay contacts to *L3*. This closes the forward contactor, at the same time forming a circuit across contact *3* of the contactor, which allows current to flow from terminal *3* on the *Rev.* button through to terminal *2* near the forward contactor, through that contactor coil, holding it closed when the *For.* button is released and returned to the position shown. Pressing the *Stop* button opens the circuit of the *For.* contactor coil, allowing that contactor to open. Then the reverse button can be pressed and a flow of current will close the *Rev.* contactor in a similar manner.

Fig. 48 illustrates connection of a typical manually operated reduced-voltage autotransformer type starter for squirrel-cage induction motors.

Fig. 49 illustrates magnetically operated one-step primary-resistance type of induction-motor starter.

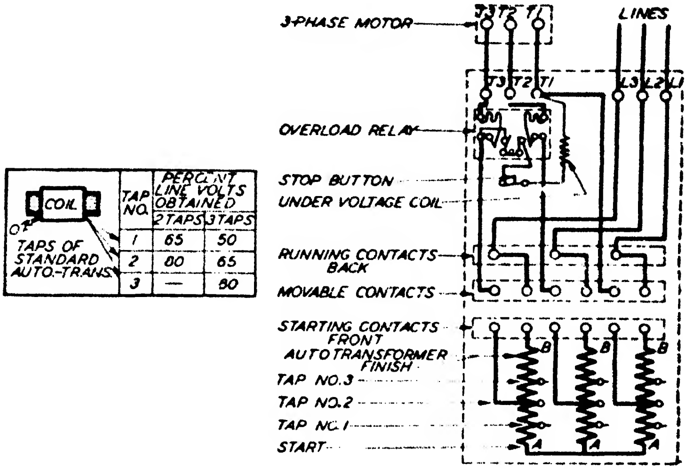


Fig 48 Connections for Manual Autotransformer Reduced Voltage Starter

Standard compensators up to 50 hp have two taps and those above 50 hp have three taps. Moving the handle of the compensator to the *Start* position causes the group of movable contacts, indicated within the dotted rectangle, to move down on top of the starting contact. Current then flows from line wires *L1*, *L2*, and *L3* directly to the upper terminal *B* of the autotransformer, through it to the Star connection at *A*. Tap No. 2 of each coil is connected to motor terminals *T1*, *T2*, and *T3* respectively. When the handle is pushed to the running position, the movable contacts slide over on top of the running contacts, connecting lines *L1*, *L2*, and *L3* directly to the motor terminals *T1*, *T2*, and *T3*. The compensator handle is held in the running position by means of a catch that can be tripped by the plunger of the under-voltage coil. The overload relay as well as the stop button can open the under-voltage coil circuit and trip out the compensator, allowing the movable contacts to return to the position shown in the diagram.

Fig. 50 shows wiring connection for a magnetically operated, reduced-voltage, autotransformer type starter.

It would be difficult to show the many types of connections required for multispeed squirrel-cage induction motors, because of the many different motor winding connections required for different torques. Therefore, only Fig. 51 is shown to illustrate a magnetic controller for a typical two-winding, two-speed induction motor, requiring the simplest type of control.

Manually operated drum controllers are also used for multispeed motors. In most instances, especially for constant-torque and con-

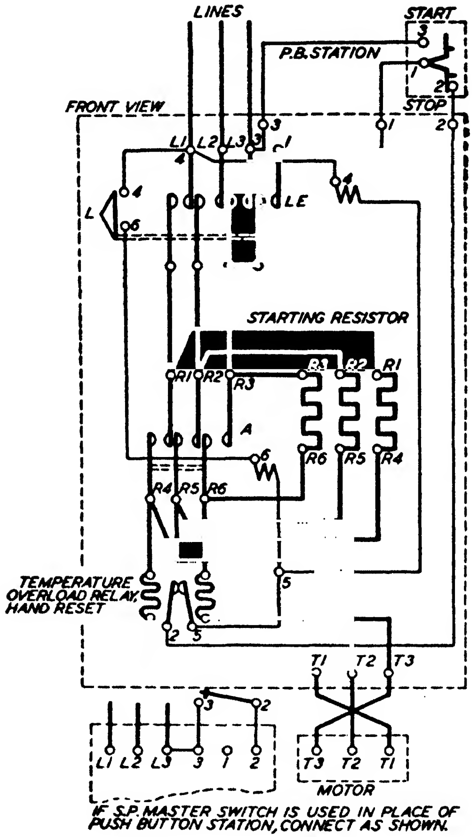


Fig. 49. Connections for Primary Resistor Type Starter

Pressing the *Start* button allows current to flow from *L1* to the line contactor coil *4*, through temperature overload relay contact *5* to *2*, through the push button, terminals *2* to *3* to line *L3*. This closes the line contactor *LE*, to lines *L1*, *L2*, and *L3*, through the starting resistor *R1–R4*, *R2-R5*, *R3-R6*, respectively, to the motor terminals *T1*, *T2*, and *T3*. Then when the timing relay *L* closes contacts 4 and *6*, current flows through coil *6* of contactor *A*. This short-circuits the starting resistance, connecting the motor directly to the line.

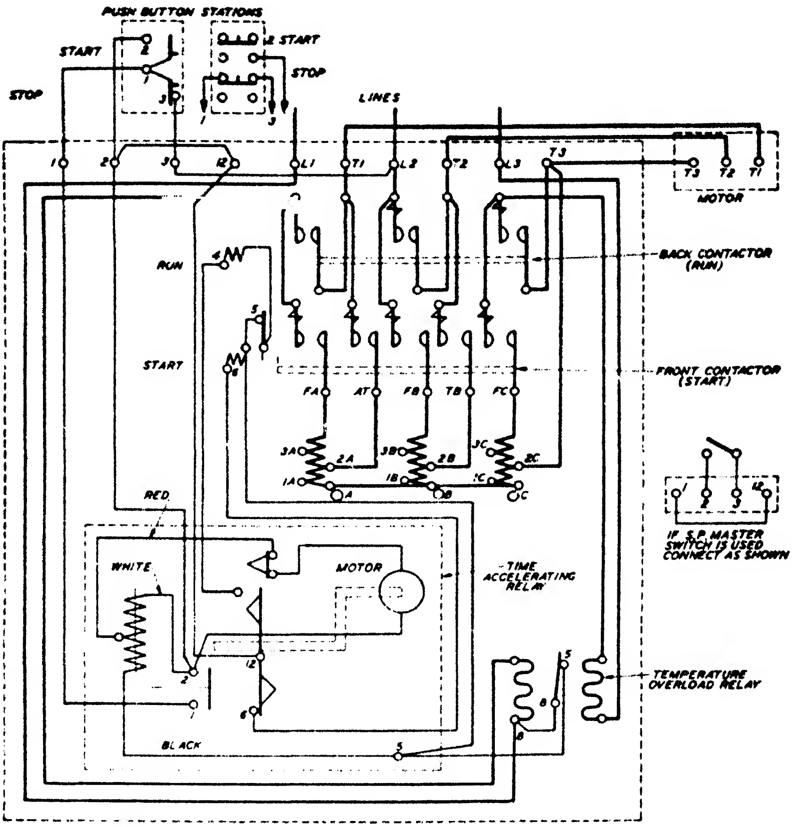


Fig. 50 Wiring Diagram for a Magnetically Operated Autotransformer Type Reduced Voltage Starter

Pressing the *Start* button allows current to flow from *L1*, through the temperature overload relay contact *8* to *5*, through the start contactor coil *6*, through the time accelerating relay contact *12*, to terminals *12* and *2* of the start button, through the push button to terminal *3* and line *L2*. Current flowing through the contactor coil *6* causes the *Start* contactor to close, connecting the lines *L1*, *L2*, and *L3* to the autotransformer coils *FA*, *FB*, and *FC*. These three coils are Star connected at points *A*, *B*, and *C*. The taps *2A*, *2B*, and *2C* are connected to motor terminals *T1* and *T2* through the contacts *AT*, and *TB*. The tap on coil *C* is connected directly from *2C* to terminal *T3*. When the *Start* push button is pressed, current also flows from line *L1* to temperature overload relay contacts *8* and *5*, through terminal *5*, through the timing relay coil to *2*, and to terminal *2* of the push button. This closes contacts *1* and *2* at the timing relay and applies voltage to the motor of the timing accelerating relay. This voltage is from the middle point on the coil below the word *White* and terminal *2*. Current going through the coil closes contacts *1* and *2*, establishing the holding circuit when *Start* button is released. When the motor of a timing accelerating relay operates, it opens contacts *12* and *6*, allowing the start contactor to return to the open position, closing the interlock *5* above contactor coil *6*. At the same time the motor closes the contacts *12* to *4* of the running contactor coil, allowing current to flow through that coil and closing the running contactor. The motor terminals *T1*, *T2*, and *T3* are connected directly to the line terminals. Taps on autotransformer are similar to those shown in left-hand view, Fig. 48.

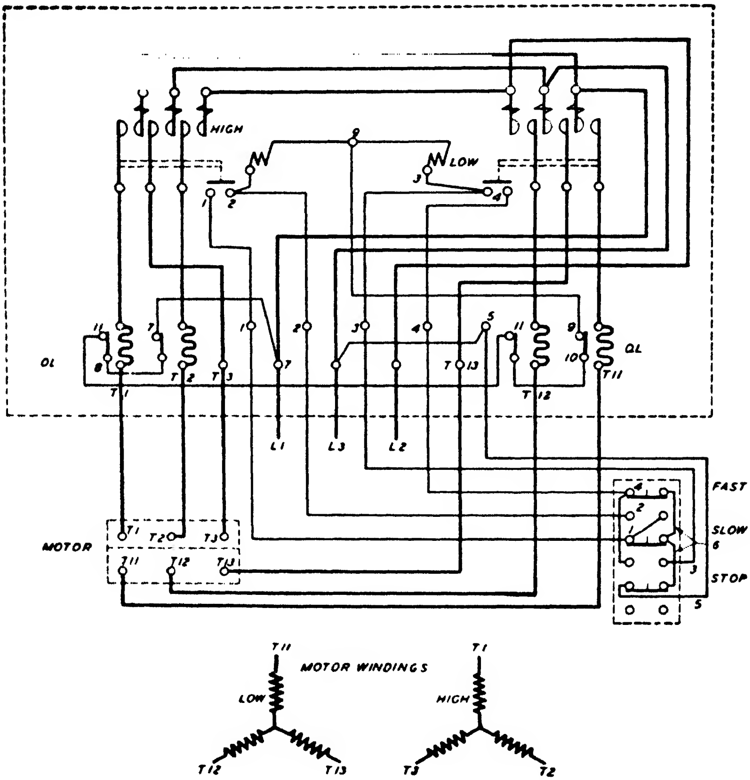


Fig. 51. Magnetic Controller Connections for Two-Speed Squirrel-Cage Induction Motor

This motor has two separate windings. The high-speed terminals are *T1*, *T2*, and *T3*. The low-speed windings are *T11*, *T12*, and *T13*. Pressing the slow speed button joins wires *3* and *4* at the push button, forming a circuit from *L1*, terminals *7*, *8*, *11*, right-hand overload relay, terminals *11*, *10*, *9*, to the low-speed contactor coil, to terminal *3* at the push button, through the *Fast* button *4*, wire *6*, stop button, wire *5*, terminal *5* to *L3*. This causes the low-speed contactor to close, connecting *L1*, *L2*, and *L3* directly to the motor terminals through the overload relay coils *OL* to motor terminals *T11*, *T12*, and *T13* respectively. When changing to high-speed, pressing the push button marked *Fast* causes current to flow from terminal *9* through the high-speed contactor coil, terminal *2* to the push button, terminal *1*, through the low-speed button terminal *6*, through the *Stop* button, wire *5*, terminal *5* and *L3*. This closes the high-speed contactor, joining the main lines *L1*, *L2*, and *L3* directly to the motor terminals *T1*, *T2*, and *T3*, through the overload relay coil and line wires *T1* and *T2*. When either the high-speed or low-speed contactor closes, contacts *1* and *2*, and contact *4* of the low-speed contactor are connected, holding that particular contactor closed when the fast or slow button is released.

stant-horsepower motors, an overload device is provided for each operating speed.

Control for Wound-Rotor Induction Motors. Fig. 52 shows the circuit of a manual-dial type secondary starting rheostat with inter-

locked primary magnetic switch, for small motors up to 20 horsepower. Since the primary switch cannot be closed until the interlock is closed, with the dial in "Resistance In" position, it is impossible to start the motor with the rings short-circuited.

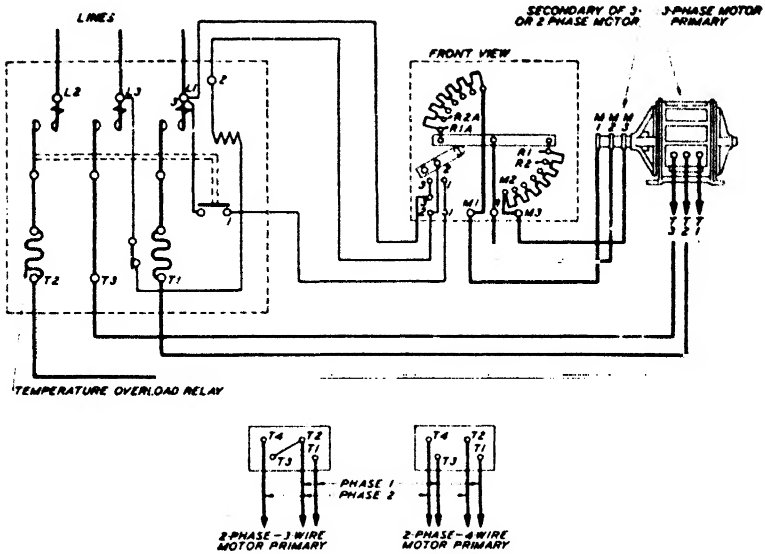


Fig. 52. Wiring Connections for Starting Small Slip-Ring Induction Motor

Pushing the small lever down on the front view of rotor resistance controller joins contacts *2* and *3*, allowing current to flow from *L1*, through contacts *3* and *2*, line contactor coil, temperature overload relay contact, to line *L3*. This closes the contactor, joining *L1*, *L2*, and *L3* through the temperature overload relay to the motor terminals *T1*, *T2*, and *T3*. When the contactor closes, *L1* is joined to control terminal *1*, thus providing a holding circuit through the contactor coil. The speed of the motor is increased by moving the rheostat bar *R1A* and *R1* clockwise, decreasing the resistance between the rotor leads *M3* and *M2* and also between *M1* and *M2*.

A simple, manually operated, dial-type control with secondary resistor for speed-regulating duty is illustrated in Fig. 53. The push-button station may be omitted and the interlock switch wired direct to the primary magnetic switch coil, if desired.

Larger motors whose secondary current per phase exceeds 100 amperes require manually operated drum switches. Fig. 54 shows connections, using either a primary magnetic switch or a primary oil circuit breaker. Both combinations use an interlock circuit to primary switch, requiring all resistance to be inserted in motor secondary before primary switch can be closed. The same wiring is used

for both starting duty and speed-regulating duty, the only difference in equipment being the resistor which is heavier duty for the continuous service required in speed-regulating duty.

Magnetically operated starters are also available for slip-ring motors, see Fig. 55. If such a control is required for speed-regulating duty, the number of contactors is increased to give more speed points, the resistor is changed to speed-regulating type, and a multi-button push-button station and additional interlocks on each contactor are

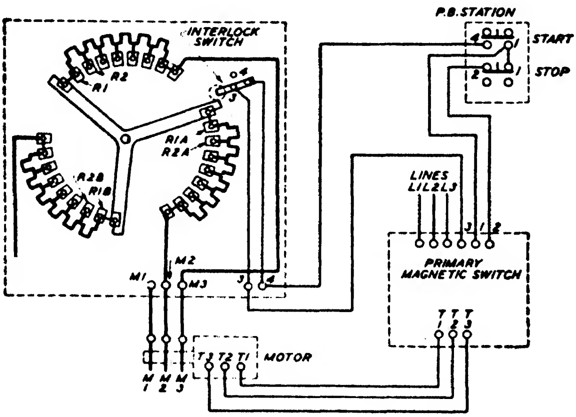


Fig. 53. Manual Speed-regulating Control for Small Slip-Ring Induction Motor

The internal connection of the primary magnetic switch is similar to Fig. 46. The speed of the motor is increased by moving the Y arm clockwise. This decreases the amount of resistance across the slip rings $M1$, $M2$, and $M3$ of the motor

used to give pre-set control. When any speed button is pressed, the control will automatically accelerate to that point and run at the pre-set speed.

Control for Synchronous Motors. Fundamentally, the same elements of control must be provided for a synchronous motor as are used with alternating-current generators, namely: main-line switch, field switch and discharge resistor, and a field rheostat. When starting a motor with this simple control, certain precautions must be exercised to insure synchronization without damage to motor or undue disturbance to line. The field switch is open, with the motor field shorted across the discharge resistance. The first operation is to close the main switch. The motor will then accelerate up to near synchronous speed, as does an induction motor. Then the field switch is

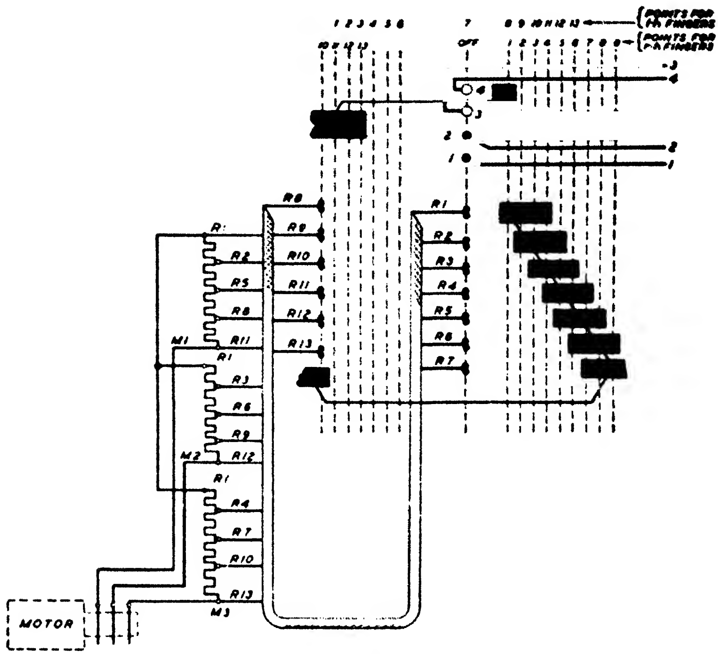


Fig. 54 Non-reversing Drum Switches and Resistors for Wound-Rotor Induction Motors with Three-Phase Secondary

This type of drum controller can be used with a primary magnetic switch like Fig. 46 or with a circuit breaker. When used with a magnetic switch, fingers 2, 3, and 4 are used. With a primary oil circuit breaker, only fingers 1 and 2 are used to provide a magnetic lock on the circuit breaker. There is no electrical connection between these four fingers and those marked *R1*, *R2*, etc. The purpose of the drum controller is to decrease the amount of resistance in steps *R1*, *R2*, *R1-R3*, *R1-R4*, then decrease the resistance *R2-R5*, etc. For tracing the circuits where the wires enter a cable, they have a similar letter and number when leaving that cable to the finger. The heavy black line represents the disks on the drum controller and the black double circle represents the fingers. The handle on the drum controller rotates the segments for the different points, of which there are 13. Each point cuts out one step of resistance in the rotor circuit, first in one phase and then the other.

closed, causing the motor to be excited as a synchronous machine, and it will pull into step or synchronism. The field excitation may then be adjusted to the required value to produce unity or leading power factor operation. If autotransformer, reduced-voltage starting equipment is used, the same procedure is followed except that the motor is accelerated on the starting step and then thrown to the full-voltage position and allowed to pull up to speed before closing the field switch and synchronizing.

Manual starting, as described, requires attendance on the part of an operator and supervision of the subsequent operation to insure

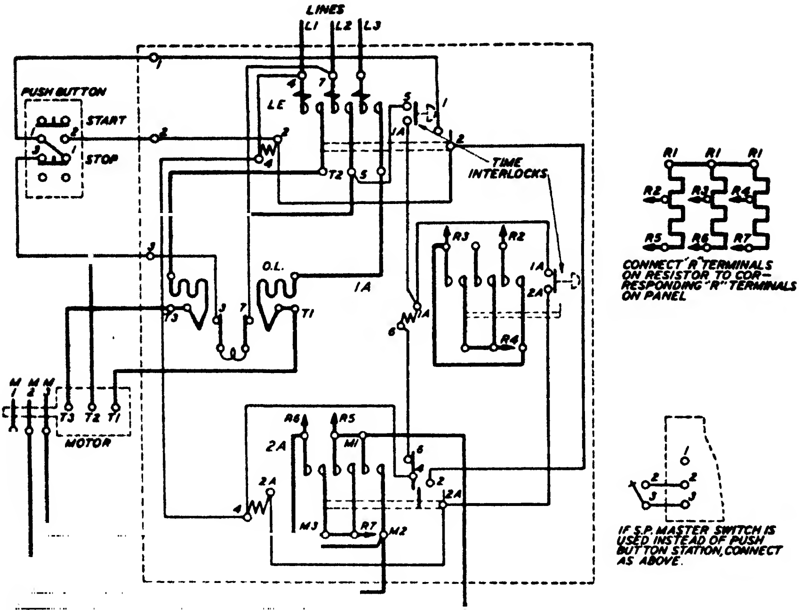


Fig. 55. Magnetic Control for Slip-Ring Induction Motor

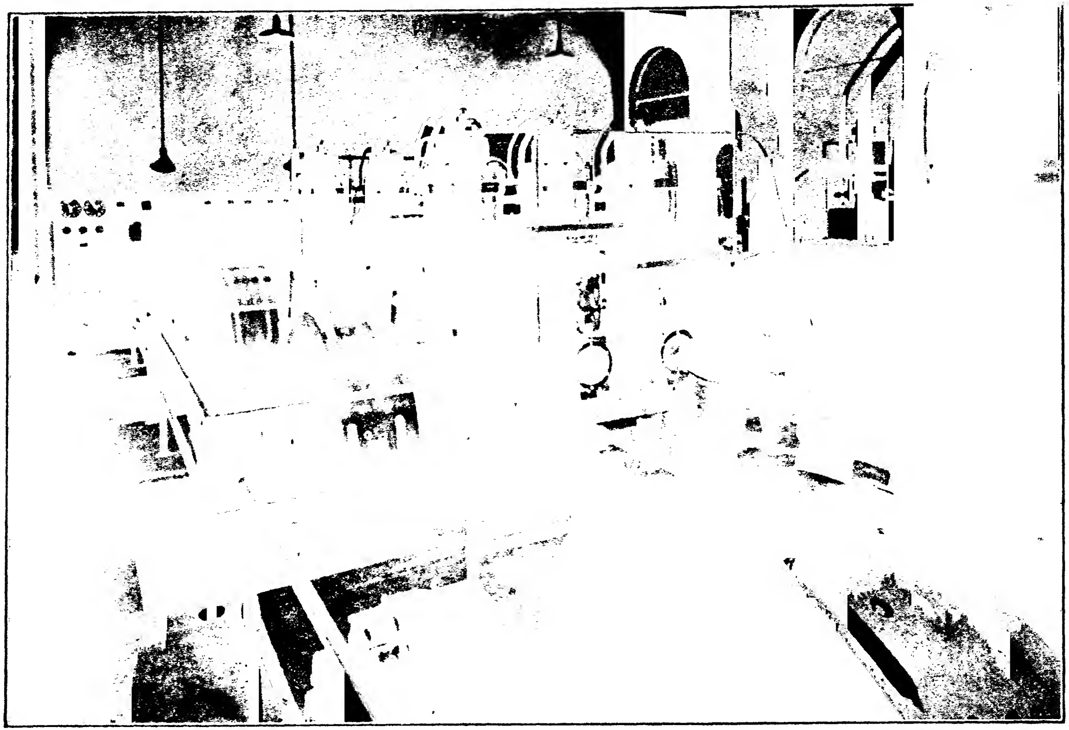
This controller starts the wound-rotor induction motor with all the resistance in the motor circuit the first step, then half the resistance cut out and finally all of the resistance cut out of the rotor circuit. This can be accomplished by pressing the *Start* button, which allows control current to flow from *L3* to terminal *4*, through line contactor coil *LE*, contact *2* of the push button, across the push button terminal, to the stop-button terminal *3*, to the *OL* contacts *3* and *7* to line *L2*. This closes the contactor *LE*, connecting lines *L1*, *L2*, and *L3* to the motor terminals *T1*, *T2*, and *T3*, through the overload relay coil. The contactor also closes contacts *1* and *2* at the right-hand end of the contactor and sets the time interlock in operation. After a set time the time interlock *5-1A* will close those contacts. This allows current to flow from line *L3* to terminal *4*, through the interlock contacts *4* and *6*, contactor coil *1A*, contacts *1A* and *5*, to line *L2*. Closing the contactor *1A* joins the terminals *R2*, *R3*, and *R4* of the resistor shown at the right, which short-circuits or cuts out of the circuit resistance *R1-R2*, *R1-R3*, and *R1-R4*.

After a brief time interval the time interlock at the right of contactor *1A* closes, allowing current to flow from line *L3*, control terminal *4*, to contactor coil *2A*, through the contact *2A* of the time interlock to *1A*, through *1A* of the time interlock on the contactor *LE* to line *L2*. This causes contactor *2A* to close. This joins resistance *R5*, *R6*, and *R7* together. This has the effect of cutting out all the resistance, or the same as short-circuiting the rotor leads *M1*, *M2*, and *M3* of the motor. When contactor *2A* closes, the lock-in contact *2* and contact *2A* on the dotted line establish a holding circuit through contactor coil *2A*. At the same time the interlock contacts *4* and *6* are opened, allowing contactor *1A* to open.

proper protection of the motor. Modern synchronous-motor control has been developed to the point where only an initial starting operation is required, such as pushing a "start" button if fully magnetic, or operating the main starting switch if semimagnetic. Subsequently and at the proper time, field application is accomplished automatically by control and timing devices. Thus an operator is relieved of the responsibility of determining sequence and timing.

DIESEL ELECTRIC PLANT OF THE CITY OF VERNON, CALIFORNIA

Each one of the five alternators are rated at 7500 kv-a. at a power factor of 80%, 7200 volts, three phase, 50 cycle. The small generator at extreme left is used to furnish direct current for the fields of the exciter, which in turn supplies direct current to the field of the large alternators. The flywheel and alternator are enclosed in metal housings.



THREE-CYLINDER BALL-MUNCIE DIESEL ENGINES DRIVING 100 KW. 327 R.P.M. 2400-VOLT IDEAL FLYWHEEL TYPE ALTERNATING-CURRENT GENERATORS AND V-BELT DRIVEN EXCITERS IN THE R.E.A. PLANT AT POPES CREEK, MARYLAND

The unit in the rear is operating. Note the standard and synchronous clocks on the switchboard.

Courtesy of The Ideal Electric & Manufacturing Company, Mansfield, Ohio

VOLTAGE REGULATION OF DIRECT-CURRENT GENERATORS

ACTION OF FIELD WINDINGS

Uniform generator voltage, regardless of changes in load, is required in most Diesel-electric plants. In the case of direct-current systems, it is a simple matter to maintain constant voltage, unless the load changes are severe and sudden. Compound-wound generators are used and the field poles are excited by two independent windings: (a) the shunt field circuit, which is connected across the main line, and (b) the series field circuit, through which is passed all of the current generated. See Fig. 1.

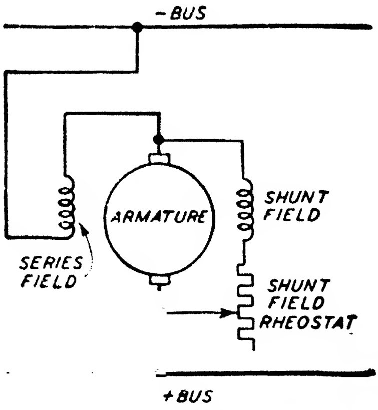


Fig. 1. Schematic Diagram of Compound-Wound Generator

Shunt Generators. The shunt field supplies sufficient magnetization for maintaining rated voltage at the generator terminals at no load, i.e., when no current is passing through the series field. However, this field excitation would be insufficient by itself to maintain rated voltage when the load increases and more current passes through the armature. The voltage would fall on account of the so-called *armature reaction* which weakens the effective field magnetism, and also because of the greater voltage loss (IR drop) in the armature

windings. In the case of a shunt-wound generator, the field can be strengthened by cutting out resistance in the field rheostat and thus increasing the shunt field current. However, this requires the operator's attention if done manually, or an additional control device if handled automatically.

Compound Generators. The series field of a compound-wound generator supplies a simple and effective solution that answers most requirements. When the load increases, the current through the series field windings becomes greater and the field magnetism automatically increases enough to hold up the voltage.

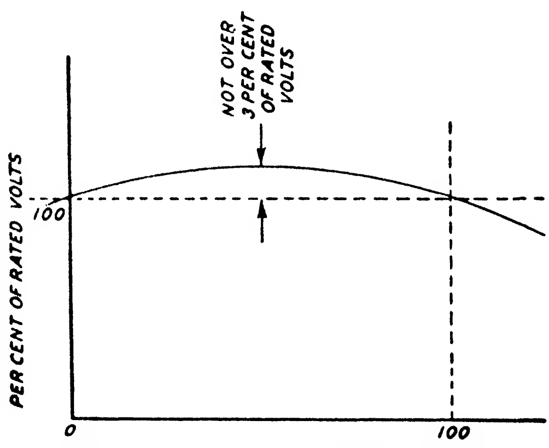


Fig. 2. Compounding Curve for D.C. Generator

Compound-wound generators are usually supplied *flat-compounded*, i.e., they will give the same voltage at full load as at no load (speed being constant). In between these limits it is not feasible to make the field strength vary at exactly the correct rate to maintain perfectly uniform voltage, and the compounding curve will rise as shown in Fig. 2. However, in standard practice the compounding curve will not vary more than three per cent from the voltage at no load or full load.

Compound-wound generators may also be *over-compounded* by increasing the strength of the series fieds, so that the voltage at full load will exceed that at no load. In this manner, voltage drop in the

distribution line may be compensated for, and constant voltage maintained at the load itself instead of at the generator terminals. Overcompounded generators generally have the following characteristics:

Terminal Voltage

No Load	Full Load
120	125
240	250

Under these conditions the compounding curve may vary somewhat more than three per cent from a straight line between no load and full load.

EXTERNAL REGULATING DEVICES

Need for Regulators. There are several applications of Diesel electric direct-current plants where compound-wound generators either will not furnish sufficiently good voltage regulation or would be unsafe without external protective devices. It will be remembered that the voltage generated by a direct-current generator is directly proportional to its speed, other factors remaining the same. Consequently, the voltage regulation of a direct-current generator and Diesel engine combination depends upon the speed regulation of the engine as well as upon the voltage regulation of the generator. Unless the engine is equipped with an isochronous governor, the speed at full load will be less than that at no load. Even if the speed is kept constant, the compounding curve is not a straight line between no load and full load (see Fig. 2); this voltage deviation may not be acceptable in certain types of service and may justify the use of an automatic voltage regulator. Such regulators are also used to obtain constant voltage from generators required to run in a wide range of speeds, such as generators connected to Diesel-driven compressors and pumps. Another common application is the control of the voltage impressed upon a storage battery that is being charged from a variable voltage source, as in railway Diesel-electric systems, where the generator is designed to develop widely different voltages in order to control the speed and torque of the traction motors.

When direct-current generators are operated in parallel, automatic voltage regulators are of further advantage in facilitating load equalization, particularly with dissimilar units, for example, units with different voltage regulation or different speed droop. Automatic regu-

lators make it unnecessary to use equalizer connections and switchgear for the series fields (see Parallel Operation); this is a particularly significant item when three-wire generators are involved. In fact, automatic regulators make it feasible to use simple shunt-wound machines (although the presence of series fields does not affect the operation with regulators).

Effect of Sudden Load Changes. When a heavy increase in load is suddenly imposed upon an ordinary compound-wound generator, the magnetic lag (hysteresis) of the field poles prevents the series field building up its strength fast enough to offset the increased voltage drop at the generator terminals. Also, the shunt field is weakened by the reduced voltage applied to it. Consequently, a momentary dip in voltage takes place until the stronger series field becomes effective. Such voltage dips are objectionable in private plants furnishing power and light to office buildings, apartment houses, etc., where a high quality of lighting service must be furnished despite sudden load changes due to the operation of elevators.

In most cases the engine speed changes much more slowly than the load does, because sudden speed changes are prevented by the inertia of the flywheel and other rotating parts. The problem of voltage dip or lamp flicker on sudden load changes is therefore an electrical one.

Automatic voltage regulators tend to reduce voltage dips caused by sudden heavy loads through their ability to force a rapid increase in field strength. When the voltage starts to fall, the regulator momentarily applies maximum field current, thus overexciting the generator for a short time until its normal voltage is restored. In this manner the time delay due to lag is shortened.

Battery Charging. Compound-wound generators, unless provided with special safeguards, are undesirable for charging storage batteries. The reason will become clear upon examination of Fig. 3 showing a compound-wound generator connected to a battery. After the battery has received charge for a time, its voltage will approach that of the generator. If now the speed of the Diesel engine driving the generator should decrease, the generator voltage may fall below that of the battery, whereupon current will flow in a reverse direction from the battery to the generator, causing the latter to deliver power to the engine. This immediately speeds up the Diesel unit enough for the engine governor to cut off the entire fuel supply. The current will continue to flow through the shunt field in the same direction, thus

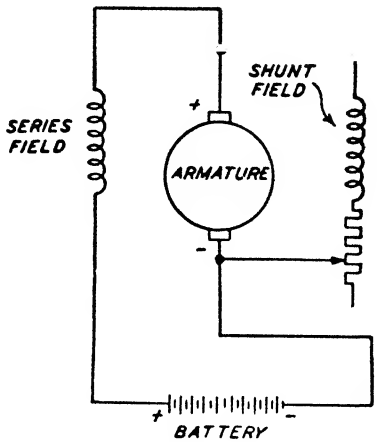


Fig. 3. Diagram of Compound-Wound Generator Connected to Storage Battery

maintaining the same polarity of the shunt field, but the series field will acquire a reverse polarity and will "buck" the shunt field. The net field strength is thus reduced and with it the generated voltage or *counterelectromotive force,* causing the unit to speed up further (like an ordinary shunt-wound motor when the field is weakened). In turn, the battery delivers a still heavier motorizing current, further strength-

Fig. 4. Carbon-Pile Regulator

Courtesy of The Safety Car Heating and Lighting Co., Inc.

ening the reverse effect of the series field. The action becomes rapidly cumulative and will end in a runaway if the net field strength is sufficient to give the required accelerating torque; or, if the net field becomes too weak, the machine will suddenly stall under heavy current flow and the powerful series field will reverse the generator's polarity. Because of these hazards, compound-wound generators, if used in storage battery service, must be provided with suitable reverse-current protection. If shunt-wound generators are used, voltage regulators are generally used to control the charging rate.

Carbon-Pile Regulators. Carbon-pile regulators are frequently used for regulating generator voltage. In this type of regulator a variable carbon resistor takes the place of the conventional hand-operated field rheostat. The carbon resistor consists of a number of thin carbon disks and is operated electrically by a solenoid and plunger through a lever mechanism which varies the pressure on the carbon pile and thus adjusts its resistance.

The self-regulating carbon pile found its most extensive use in the railroad car-lighting field as a control for generator and lamp voltage, and for battery charge. Being simple and rugged, low in first cost and maintenance cost, its use has now spread to other fields.

In Fig. 4 is shown a small carbon-pile regulator as built by The Safety Car Heating and Lighting Co. The carbon pile consists of two sets of disks $1\frac{7}{8}''$ diameter and $\frac{1}{64}''$ thick, with a capacity of 150 watts, and a resistance with the piles connected in parallel ranging from a minimum of 2 ohms to a maximum of 20 to 70 ohms, depending on the voltage drop across the pile. The pressure on the piles of disks depends upon the pull exerted by the solenoid, shown at the extreme left in Fig. 4. The pull of the solenoid varies with the current passing through the coil, which in turn depends upon the voltage of the circuit to which the solenoid is connected.

All parts of the regulator are mechanically balanced, the necessary resisting forces being obtained from springs. This gives constant and close regulation in spite of jars or movements incidental to service, and eliminates heavy liquid dashpots. The dashpots used are of the inverted air type with graphite plungers. It is claimed that these dashpots are constant in action winter and summer, regardless of temperature changes, and do not become clogged with the dust of service.

Variation in the regulated voltage due to heating of the voltage coil is limited to five per cent by inserting a zero-heat-coefficient re-

sistance in series with the coil. Closer compensation can be had when necessary. Adjustment is provided so that any desired voltage may be obtained within the limits of the regulator. A schematic wiring diagram showing the application of a carbon-pile regulator for controlling generator voltages is shown in Fig. 5.

The generator in this case is controlled to give the proper voltage throughout changing speeds and loads by the amount of current supplied to the shunt field. This field current is controlled by the resistance of the carbon pile in series with the field. The resistance

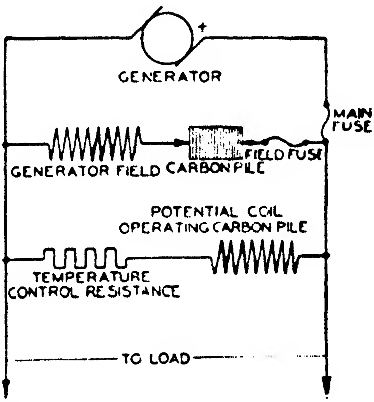


Fig. 5. Schematic Wiring Diagram of Carbon-Pile Regulator Controlling Shunt Wound Generator
Courtesy of The Safety Car Heating and Lighting Co., Inc.

of this carbon pile is governed by the pressure exerted upon it by a lever which is operated by a plunger of the potential coil. If the voltage tends to rise above that which the regulator is set to maintain, the voltage coil, through its lever, reduces the pressure on the carbon pile and holds the voltage to its proper value.

Carbon-pile regulators can also be used with compound-wound generators by using an extra, current-responsive winding on the voltage coil. A typical wiring diagram is shown in Fig. 6. It will be noted that the extra winding is shunted across part of the series field wiring.

The application of a carbon-pile regulator to control a battery charge from a variable source of voltage is shown in Fig. 7. In this case, the carbon pile is connected in series with the battery, and is

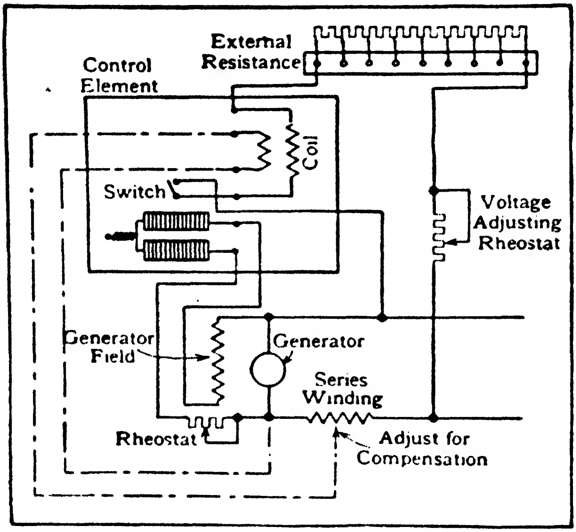


Fig. 6. Schematic Wiring Diagram of Westinghouse Carbon-Pile Regulator Controlling Compound-Wound Generator

Courtesy of Westinghouse Electric and Manufacturing Co.

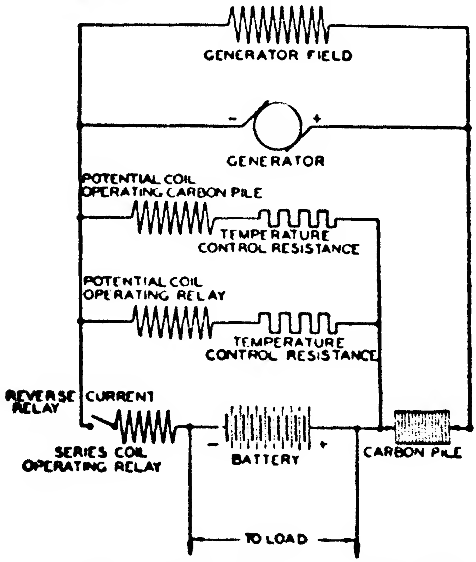


Fig. 7. Wiring Diagram of Carbon-Pile Regulator Controlling Battery Charge

Courtesy of The Safety Car Heating and Lighting Co., Inc.

also equipped with a reverse current relay for disconnecting the battery from the generator when its voltage is below that of the battery. The charge in this case is controlled by the voltage only, although if desired, some current control can be used. The potential coil is connected across the battery when the reverse current relay is closed, and if the generator voltage is higher than that which it is desired to maintain across the battery terminals, the plunger of the solenoid will move, and thereby increase the resistance of the carbon pile until the desired potential is obtained. With a decrease in voltage at the battery, the opposite action takes place.

Vibrating-Type Regulators. Vibrating-type voltage regulators are sometimes used for direct-current generators supplying lighting and power loads where the power load is subject to sudden changes and would otherwise cause considerable flicker in the lights. They operate on the principle that when a regulating resistor is short-circuited a large voltage is available to bring the exciting current quickly to the desired value. The action consists of rapidly cutting in and out a resistance in the generator field circuit by means of vibrating contacts.

In the case of very small machines, the field resistance may be shunted directly by the main contacts of the control element. However, where the field current is large or where more than one generator is to be controlled by the same regulator, the field rheostats are shunted by the contacts of secondary relays that are controlled by the main control element.

Vibrating-type regulators in general apply corrective action to restore voltage more quickly and more powerfully than the action of the series field of an unregulated generator or that of most of the simpler forms of direct-current voltage regulators. In turn, the generator itself responds more quickly, and steadiness of the voltage is greatly improved.

This type of regulation has good sensitivity; that is, the regulator will respond to small voltage changes, and if the load is steady or changes gradually, the regulator will hold the voltage within a small zone. When expressed as a percentage of the normal voltage, this zone is called the *sensitivity* of the regulator. However, if the load changes too suddenly, the voltage will momentarily leave the sensitivity zone, even though the regulator immediately applies corrective action and eventually restores the voltage to normal. The reason for this is the time lag of the generator itself, which is quite independent of the regulator. For any given regulator, the magnitude and rate of

load change determines how far the voltage will depart from the sensitivity zone, and the time constant of the generator determines the time required to restore it to normal. The performance of the generator and regulator *combination* under specified conditions of rapid load changes is termed the *overall regulation.*

For this reason, where load fluctuations are sudden and relatively large, such as those caused by the starting of large elevator motors in small generating plants, even the most sensitive voltage regulators

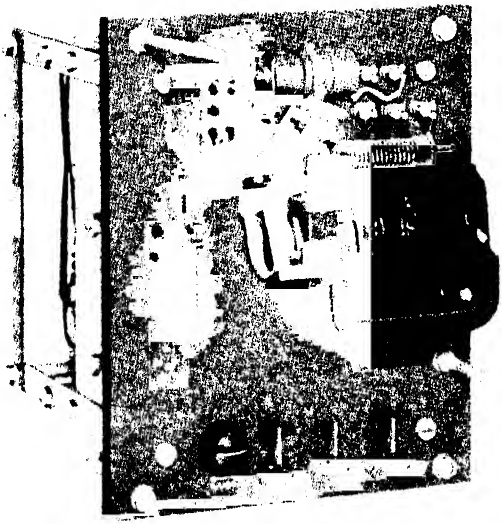


Fig. 8. Westinghouse Type UV-DG Vibrating Regulator
Courtesy of Westinghouse Electric and Manufacturing Co.

cannot entirely eliminate the flickering of lights supplied from the same bus.

Operation without Relays. A simple form of vibrating-type regulator known as Westinghouse Type UV-DG is shown in Fig. 8. It consists of stationary main and antihunting coils, a moving coil which is directly connected to the center shunting contact, and two stationary contacts. The three contacts are relatively large in size, and have contact faces of silver to graphite. This contact combination, with correct polarity, tends to keep the contact surfaces clean and prevents sticking or welding.

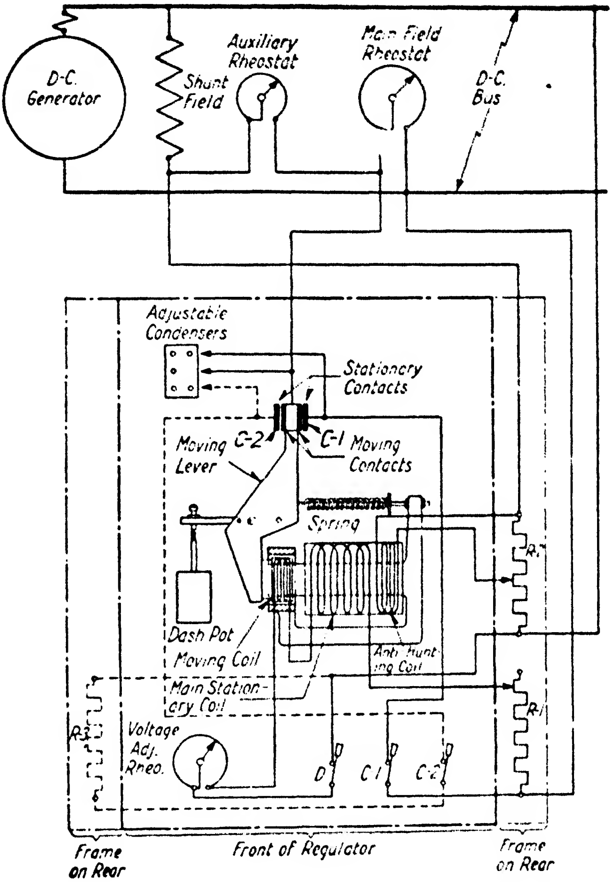


Fig. 9. Pictorial Wiring Diagram of Westinghouse Type UV-DG Regulator

Courtesy of Westinghouse Electric and Manufacturing Co.

The magnetic circuit consists of a soft iron casting, the core of the stationary coils extending into the moving coil, which is wound on a nonmagnetic spool. A spring closes the right and center contacts, and the pull of the moving coil separates them. The right and center contacts shunt the field rheostat; and on applications requiring wider ranges, the center and left contacts shunt the field through a resistor.

Fig. 9 is a pictorial wiring diagram and Fig. 10 a schematic diagram of this regulator. Upon a fall in generator voltage the attraction of

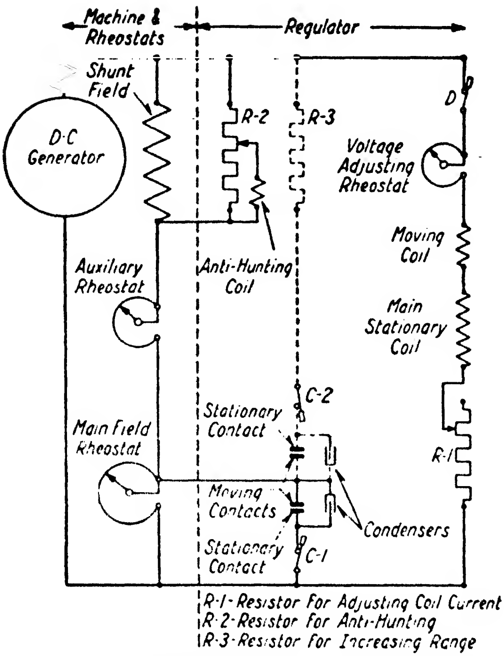


Fig. 10. Schematic Diagram of Westinghouse Type UV-DG Regulator
Courtesy of Westinghouse Electric and Manufacturing Co.

the stationary and moving coils is weakened, whereupon the spring closes contact *C-1* and thus short-circuits the main field rheostat, increasing the field current. *R-3* (not always used) is a resistor which, when contact *C-2* is closed by rising voltage, shunts the generator field itself; it thus broadens the range of the regulator. *R-1* is a resistor in series with the stationary and moving coils which reduces the effect of temperature; it is also used for adjusting voltage.

The regulator is stabilized by a stationary antihunting coil and an adjustable resistor *(R-2)*, which are in parallel with the generator shunt field. Their action is as follows: When a decrease in voltage causes contact *C-1* to close, the current through the shunt-field circuit is increased, causing more current to pass through the antihunting coil and increasing the attraction between the stationary and moving coils. This causes contact *C-1* to open at once and reverse the action, so that a continuous rapid vibration is produced. The action, in principle, is similar to the interrupter used in an ordinary bell or

buzzer. The effect of the generator voltage on this continuous vibration is to vary the ratio of the time that contact *C-1* is closed to the total time of each cycle of vibration. This action gives the field rheostat what is termed *effective resistance*, which in turn determines the generated voltage.

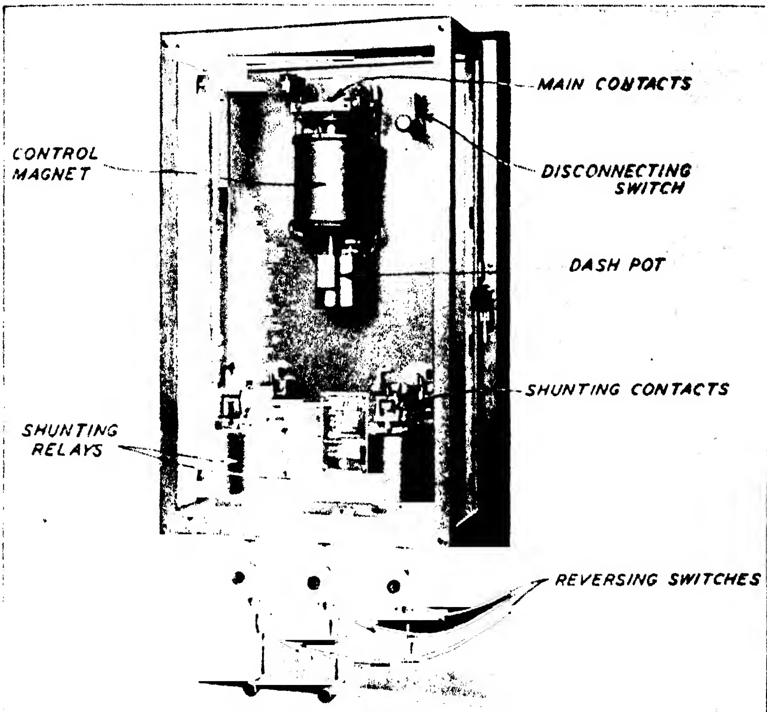


Fig. 11. Westinghouse Relay-Type Voltage Regulator
Courtesy of Westinghouse Electric and Manufacturing Co.

Condensers are used across the contacts to prevent sparking. A liquid-type dashpot is connected to the end of the lever arm by a helical spring. The spring permits the normal minute oscillations to take place freely without restriction by the dashpot, which is intended to function only when an actual change in load occurs.

This type of vibrating-contact regulator is simple, compact and comparatively inexpensive. It is little affected by shock, tilt, external vibration or change in position. It is therefore adapted for use on Diesel-electric shovels, dredges, portable plants and marine and rail-

way service. Because of its single contactor, it cannot be used to control more than one generator. The rated sensitivity (defined previously) is plus or minus two per cent of normal voltage.

Operation with Relays. For large-sized machines, for closer voltage control or for controlling paralleled generators from a single regulator, a more elaborate form of vibrating-contact regulator is used. This

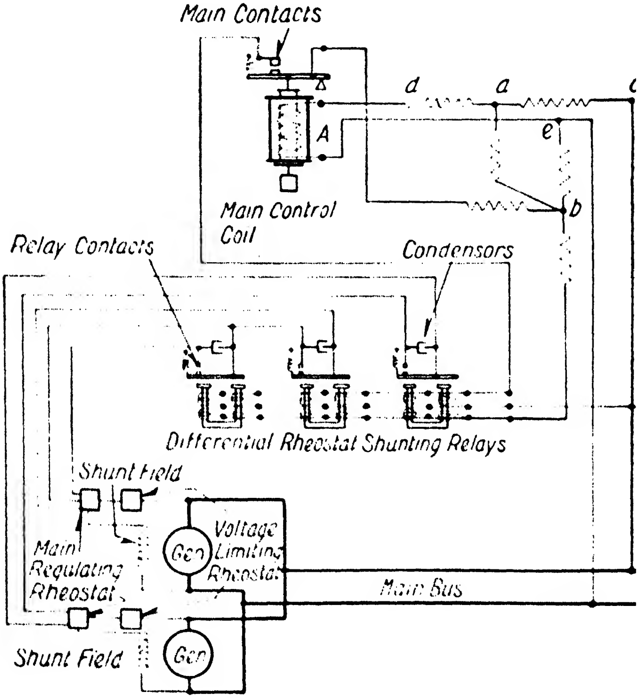


Fig. 12. Wiring Diagram of Westinghouse Relay-Type Regulator

Courtesy of Westinghouse Electric and Manufacturing Co

incorporates precious-metal main contacts on the control element and secondary shunting relays for the generator field rheostats. Generally up to three shunting relays can be controlled by the contacts of the main control element; if a greater number of relays must be controlled, a master relay is used, the contacts of which control the shunting relays.

Fig. 11 illustrates the Westinghouse form of direct-current voltage regulator with relays, known as Type DB. The schematic wiring

diagram, Fig. 12, shows the control element winding energized from the main bus. The shunting relays have two coils and each coil has two windings, the polarity of one winding bucking that of the other. The one winding is constantly energized from the main bus and tends to hold the relay contacts open. The other winding is energized only when the main or master relay contacts are closed. When it is energized, the pull of the other winding is neutralized, allowing the spring to close the contacts.

Disregarding for the moment the effect of the antihunting or vibrating connection *a-b*, when the voltage on the main bus rises, the current in the main control coil is increased, causing the main contacts to open. This in turn opens one circuit of the shunting relay coils, allowing the other circuit to open the shunting relay contacts, thus inserting resistance in the field circuit of the machine. This causes the bus voltage to fall, which, in turn, decreases the current in the main control coil, allowing the main contacts to close. When the main contacts close, the second circuit of the shunting relays is made, neutralizing the first and allowing the relay contacts to close. This short-circuits the field rheostat, which raises the bus voltage, and the cycle is repeated. The purpose of the vibrating connection is to speed up the action by causing the main contacts to operate even before the regulator has had time to go through the whole cycle of voltage regulation just described. This is accomplished by the resistor between points *a* and *b*. The resistances between points *c-a-d-b* are so proportioned that when the main contacts close and the second circuit of the shunting relays is made, the current in the main control coil is increased, which tends to open the main contacts at once without waiting for a rise in bus voltage. This is due to the fact that when both relay circuits are made, the difference between the potential of points *a* and *b* is decreased, thus decreasing the current in circuit *a-b* and increasing the current in the main control coil.

Direct, Quick-acting Regulators. Among the latest types of voltage regulators developed to give high-quality performance under severe load conditions is the quick-acting rheostatic type regulator. In this type the moving element has low inertia owing to lightweight construction, which, combined with maximum travel of only a fraction of an inch, enables it to move rapidly through its entire range when necessary.

These regulators vary directly the resistance in the field circuit, operating only when a correction in voltage is necessary. There are

no vibrating contacts, so that this item of maintenance and replacement is eliminated.

An example of the direct, quick-acting type of voltage regulator is the Westinghouse "Silverstat" shown in Fig. 13 with front cover removed. In this regulator the moving element is a series of silver buttons, each mounted at the free end of an individual leaf spring of

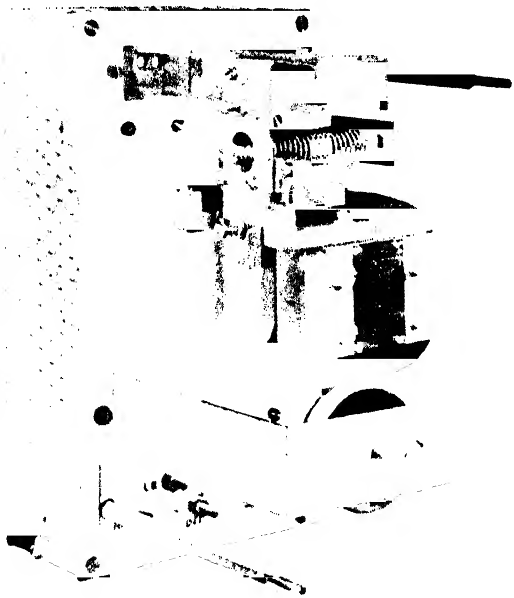


Fig. 13. Westinghouse "Silverstat" Regulator with Cover Removed
Courtesy of Westinghouse Electric and Manufacturing Co.

conducting material. The other end of the leaf spring is fixed, and the assembly holding the fixed ends is arranged so that each is individually insulated from the others. Each silver button is connected electrically by means of a wire stretching from the fixed end of its leaf spring to a tap on a stationary regulating resistance. The silver buttons are in this manner connected in sequence to consecutive taps or steps of the regulating resistance. The leaf-spring assembly appears in the upper part of Fig. 14, which shows diagrammatically the construction of the main control element used in these regulators.

The voltage to be regulated is applied to a stationary coil that is mounted on an iron magnetic circuit containing an air gap in which an iron armature can move. The armature is attached to the lower end of a moving arm, its pull being resisted by a spring. (See Fig. 14.) The upper end of the moving arm makes mechanical contact with the free end of the leaf-spring assembly. Thus any change in voltage

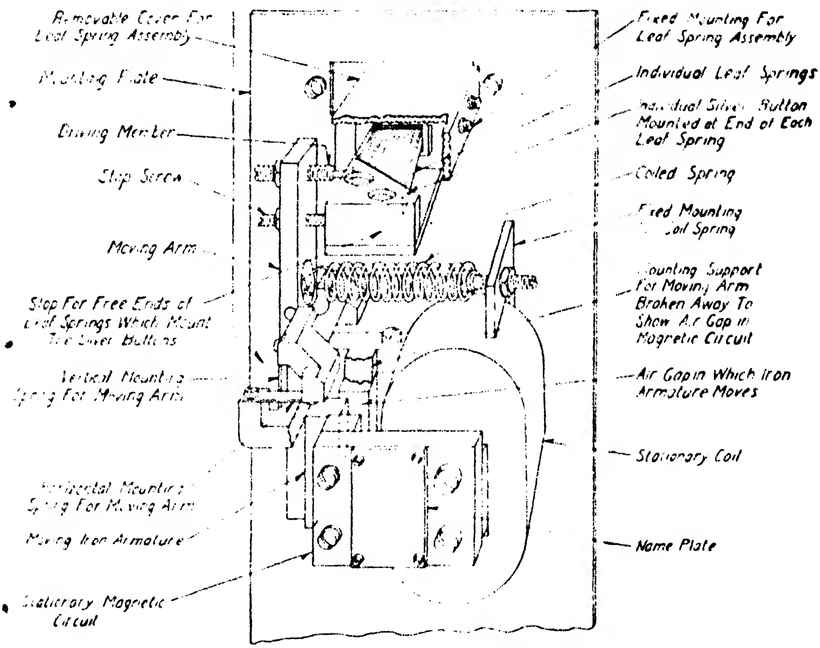


Fig. 14. Pictorial Diagram of Main Control Element of Westinghouse "Silverstat" Regulator
Courtesy of Westinghouse Electric and Manufacturing Co.

changes the position of the moving arm, which in turn applies more (or less) pressure to the leaf springs, causing more (or less) of the silver buttons to make contact in succession. At one end of the travel of the moving arm, all of the silver buttons are separated from each other, placing maximum resistance in the field circuit. At the other end of its travel all of the silver buttons are closed, thus shorting out the resistance in the field circuit through a silver path and cutting resistance to a negligible value. Since the moving arm has a short

travel, all resistance can be inserted or cut out quickly or it can be varied gradually, depending on the change in excitation required. It is claimed, in fact, that the resistance is not changed step by step when the silver buttons make or break contact, but that because there is a progressive change in pressure between the faces of the buttons, their contact resistance varies, and this effect combined with the small value of resistance per step acts to produce a completely smooth variation from practically zero resistance to the maximum.

Other interesting features are the mounting of the moving arm on supporting springs and the complete absence of pivots and bearings in the entire regulator.

To stabilize the regulated voltage and prevent excessive swinging under various conditions of excitation change, a damping effect is introduced into the regulator coil circuit by means of a damping transformer. The use of this device eliminates the need for dashpots or similar mechanical antihunting devices. One winding of the damping transformer is connected across the shunt field of the generator. (See Fig. 15.) The other winding is connected in series with the regulator coil. When there is a change in excitation voltage as a result of the regulating action of the regulator, there is an induced transfer of energy from one wind to the other of the damping transformer. The energy thus introduced into the circuit of the regulator coil acts, by reason of its direction, magnitude, and time, to electrically damp excessive action of the moving arm, thus preventing the moving arm from carrying the change in regulating resistance (and consequent change in excitation) too far. The damping transformer operates only when the generator excitation is changing; at other times the steady current passing through it has no effect.

Parallel Operation. These regulators are limited to the control of only one direct-current generator at a time, whether the generator be self-excited or separately excited from a constant source of potential. Where such direct-current generators operate in parallel the recommended practice is to provide each generator with an individual regulator equipped with a compensating winding to control the sharing of load between the several generators.

General Electric "Diactor" Regulator. Another form of direct-acting, rheostatic regulator is the Diactor type built by General Electric Company and known as Type GDD for direct-current use. The Diactor regulator differs from the Westinghouse Silverstat primarily in the design of the rheostatic element itself. Whereas in the Silver-

stat the voltage-sensitive element acts on a series of silver buttons mounted on leaf springs individually wired to taps on a ***stationary*** resistance, the Diactor voltage-sensitive element acts directly on stacks

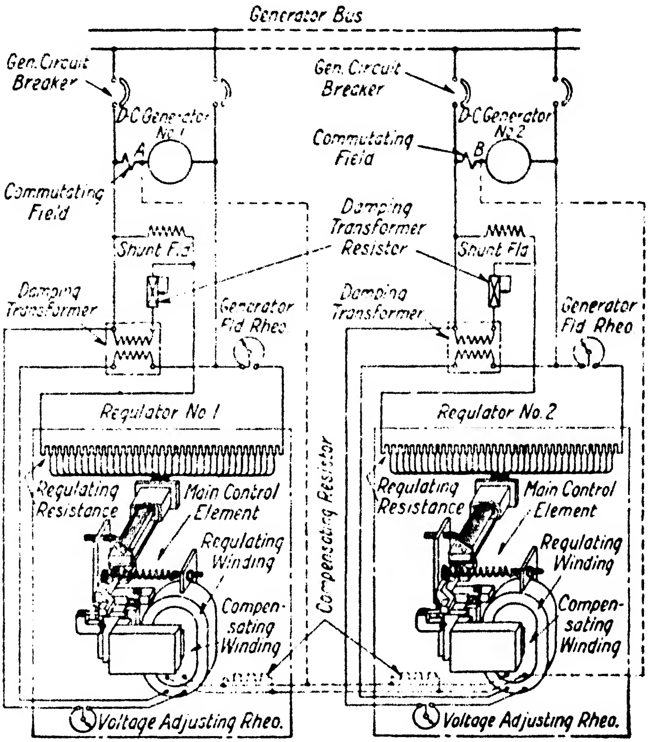


Fig. 15. Pictograph Wiring Diagram, Westinghouse "Silverstat" Regulator

Solid line connections apply for single generators. When direct-current generators operate in parallel, dashed connections are added.

Courtesy of Westinghouse Electric and Manufacturing Co.

of pivoted resistance plates and tilts them in such manner as to change the length of the resistance path through them.

A striking example of the many different ways in which direct-current voltage regulators can be applied is their availability as *frequency* regulators in cases where shunt-wound or compound-wound direct-current motors are employed to drive alternating-current generators. The regulator winding is connected to one phase of the

alternating-current generator terminals through a frequency-indicating transformer and a copper-oxide rectifier, as shown in Fig. 16 for a General Electric regulator. The frequency-indicating transformer is so constructed that the voltage appearing across its secondary is proportional to the frequency of the alternating-current generator output

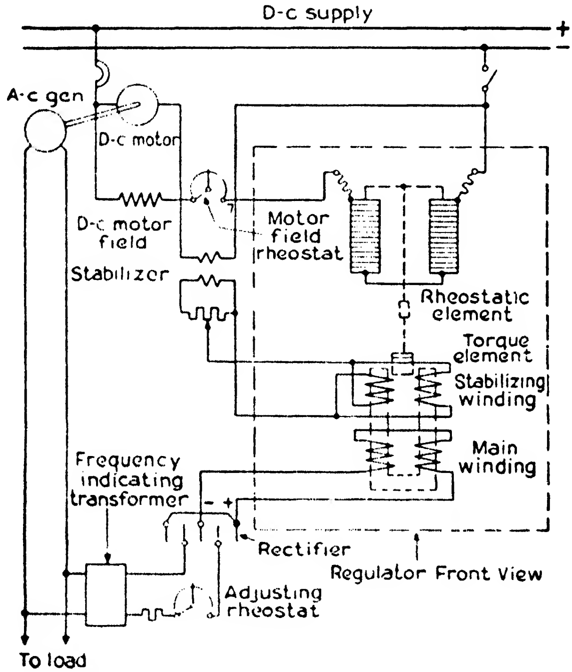


Fig. 16. Schematic Wiring Diagram, General Electric "Diactor" Frequency Regulator

Courtesy of General Electric Company

and is independent of the alternating-current line voltage if the latter does not vary more than 10 per cent from normal. Ordinary alterating-current voltage fluctuations do not affect it. Thus, when the frequency rises above normal the increased voltage on the voltage regulator causes it to decrease the resistance in its rheostatic element, which in turn increases the strength of the direct-current motor field and decreases the motor speed. A reverse action takes place on a drop in frequency.

ELIMINATING VOLTAGE DIP BY USING STORAGE BATTERY

It has been mentioned previously that a voltage regulator, however sensitive, can do no more than quickly and powerfully to apply corrective action to the generator when a change in voltage occurs. If the load change is large and sudden, the voltage will depart from normal; and the time required to restore it after the regulator has acted depends upon the time constant of the generator.

One method of eliminating the delay caused by magnetic lag in the generator (employed where high quality lighting service must be furnished despite a "rough" load) is to use a storage battery floating on the line in parallel with the generator and the load. When the load

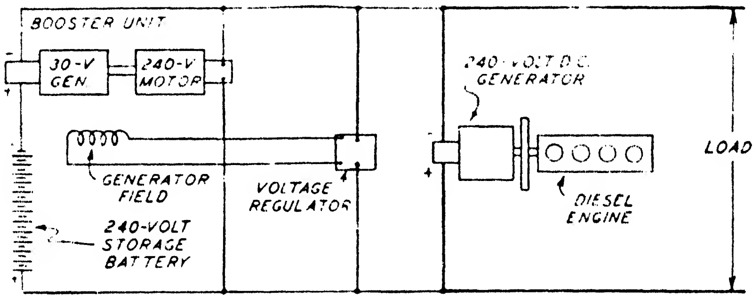


Fig. 17. Simplified Diagram of Controlled Booster System for Regulating D.C. Voltage

is suddenly increased and the generator voltage falls, the battery takes over part of the additional load. Since the load on the generator does not increase greatly, its terminal voltage does not suffer the drop it otherwise would.

A further refinement of the storage battery plan is to use a controlled *booster* between the battery and the bus. This method, which is highly effective, is shown in simplified form in Fig. 17. In the system employed by C. F. Strong for automatic Diesel plants, the booster consists of a 30-volt generator driven by a 240-volt motor supplied directly from the main bus and in continuous operation. The field circuit of the generator is controlled by a voltage regulator in such manner that both the strength and the polarity of the booster field is determined by the main line voltage. Whenever a sudden load is imposed upon the generating unit and the voltage tends to drop, the voltage regulator increases the strength of the booster generator

field in a positive direction, thus adding the booster voltage to that of the storage battery. Since the combined voltage then greatly exceeds the bus bar potential, the battery immediately delivers to the bus practically all of the additional current required to maintain full voltage on the line. In other words, the boosting of the battery voltage causes the energy increment to be drawn from the battery instead of the engine-driven generator and prevents the voltage dip that would otherwise occur.

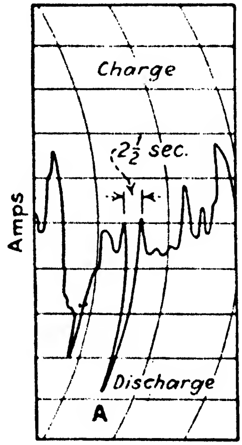


Fig. 18. Chart Showing Current Flow between Storage Battery and Main Bus

On the other hand, whenever surplus generating energy is available, as when the load falls off suddenly, the polarity of the battery booster is reversed by the voltage regulator, causing the surplus energy to be absorbed by the battery instead of momentarily raising the line voltage. The voltage regulator is so adjusted that the battery remains fully charged while a continuous succession of short-time charges and discharges goes on.

The actual performance ot this system of voltage control is shown in the accompanying graphs from a 720-kilowatt, 240-volt Diesel-electric plant equipped with a 1,380 ampere-hour 240-volt battery and a 30-kilowatt, 30-volt booster. Fig. 18 is a high-speed chart of the current flow between the battery and the main bus. This shows a swing of 196 kilowatts at the point marked A, which is absorbed by the battery system in order to stabilize the voltage. The total period

of this swing, from 0 to 196 kilowatts and back to 0 again, occupied only $2\frac{1}{2}$ seconds. The balance of the curve shows the alternating swings of charge and discharge on the battery.

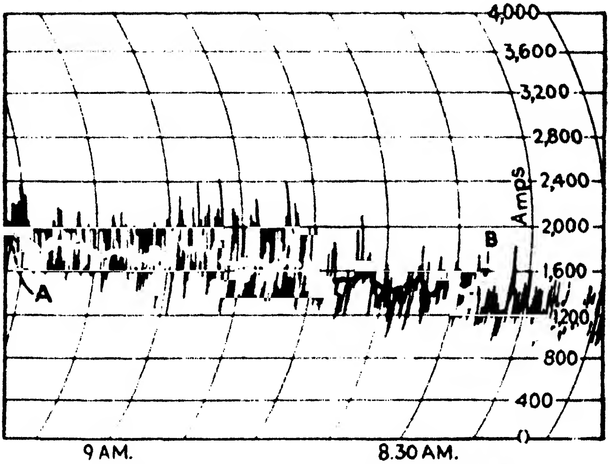
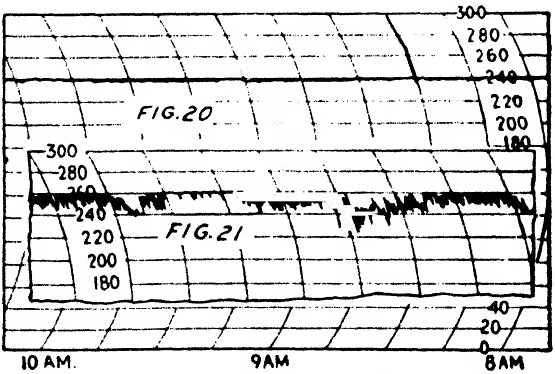
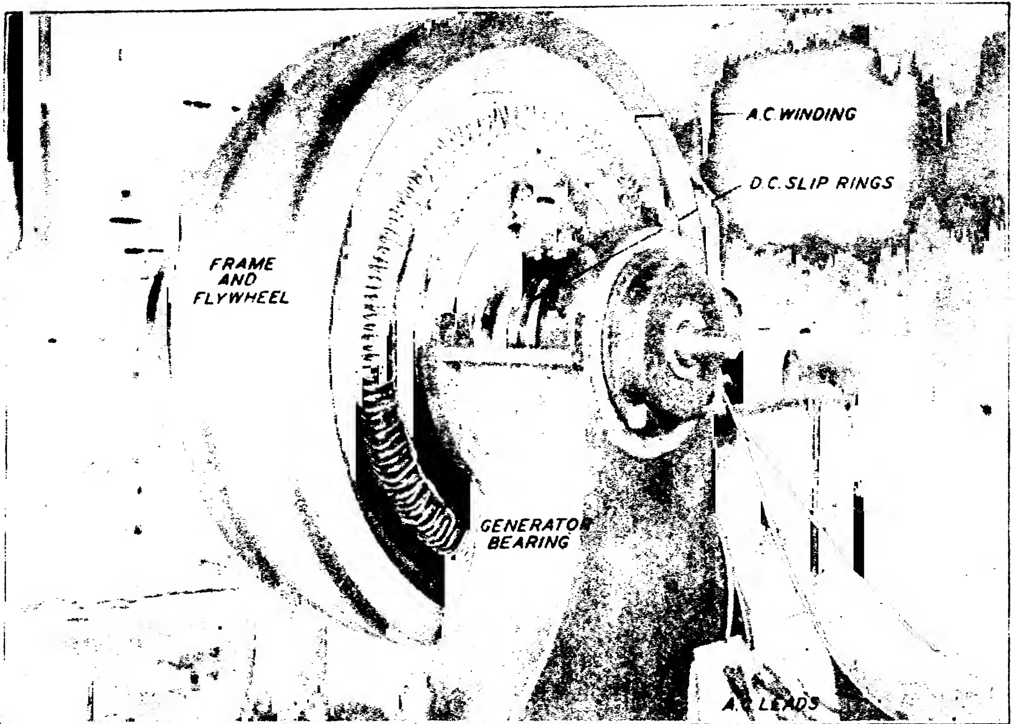


Fig. 19. Chart Showing Load Variations

On the chart shown in Fig. 19, line *AB* shows the average load carried by the engines. The energy above this line is supplied by the battery and that below is absorbed. A graph of the line voltage, Fig. 20, clearly indicates the very close regulation secured, and Fig. 21 shows a corresponding graph of the battery voltage caused by the booster in order to secure these results.



Figs. 20 and 21. Curves Showing Line and Battery Voltage



TESTING THE POPES CREEK (MD.) R.E.A. FLYWHEEL GENERATOR AT THE MANUFACTURER'S PLANT

In this type the armature windings are on the inside and stationary, and the field coils and frame rotate.

Courtesy of The Ideal Electric & Manufacturing Company, Mansfield, Ohio

VOLTAGE REGULATION OF ALTERNATING-CURRENT GENERATORS

The compounding principle, which in the case of direct-current generators is a simple and effective means of maintaining constant voltage at different loads, cannot be used for alternating-current machines. The main reason is that all field coils of an alternating-current generator must be magnetized with direct current, whereas only alternating current would be available for a series winding.

The inherent voltage regulation of alternating-current generators is quite poor. A standard 50° C. rise generator, 80 per cent power factor, when supplied with constant exciting current, will suffer a voltage drop of about 40 per cent at its terminals when the load increases from no load to full load. Voltage variations of this magnitude are of course out of the question in most applications. Although the voltage could be controlled by manually operating the generator and exciter field rheostats and thus altering the amount of excitation current, such operation would not be feasible except in the rare cases of loads that are perfectly steady or that change seldom and at predetermined times.

Automatic voltage regulators are therefore required on most alternating-current installations. This problem has engaged the attention of inventors and designers for the last fifty years, and a wide variety of devices has been developed. While there are now in use many different forms of alternating-current voltage regulators, almost all of them control the current in either the alternator field or the exciter field by one of three methods or, in some cases, a combination of two of them. The *rheostatic type* controls the field current by varying in small steps the amount of resistance in the field circuit. The *vibrating-contact type*, known in some forms as the *Tirrill type*, continuously closes and opens a short circuit around a regulating resistor in the excitation circuit, the effective excitation depending upon the proportion of the time the resistor is short-circuited. The *electronic type* uses electronic tubes to rectify part of the alternating-current generator output to furnish direct current to either the shunt field of the exciter or the field of the alternating-current generator itself, the

amount of excitation current being controlled electronically in accordance with the generator voltage. Combination rheostatic-vibrating types use a motor to move the field rheostat to a new position, and also a vibrating contact to short-circuit the field rheostat during the interval while the field rheostat is assuming its new position.

RHEOSTATIC TYPE VOLTAGE REGULATORS

Rheostatic type voltage regulators vary widely in design, from simple types that are intended for less exacting service, to more complicated constructions suitable for quicker action and more accurate control. Some rheostatic type regulators are described herewith.

Motor-Driven Rheostat Regulator. The Swam Automatic Voltage Adjuster, shown in Fig. 1, is designed for small isolated electric plants and is simple, sturdy, and easily adjusted. The principle of operation is a field rheostat operated by a series motor, which in turn is controlled by a special type of voltage relay in which contacts are made and broken with mercury switches.

The diagram of connections is shown in Fig. 2. The operation is simple, in that the armature floating in the field of the alternating-current potential coil always remains in the same position with the same voltage. Should the voltage rise, due to a reduction in load, the armature rises and trips a mercury switch which, in turn, connects the operating motor to its source of current, causing the motor to run clockwise, thus cutting in resistance on the exciter field. As soon as sufficient resistance is cut in, the voltage will return to normal and the mercury switch contact is broken. The motor then stops and awaits another change in voltage.

In order to obtain stable regulation, provision is made to adjust the speed of the operating motor so that the regulating resistance will be changed at a somewhat slower rate than the speed of response of the exciter and generator. In this manner, hunting or overregulation is avoided. The speed of the operating motor is adjusted by means of resistances R-1 and R-2 (Fig. 2), separate resistances being used so that the *Up* speed can be adjusted independently of the *Down* speed. The operating motor speed can be adjusted so that the rheostat is moved through its full range in from 45 seconds to two minutes. This rate of response obviously would be too slow to give good voltage regulation in plants where there are sudden large changes in load.

A hand wheel on the front is connected with the gear wheel by means of a clutch, so that for quick starting hand control is provided.

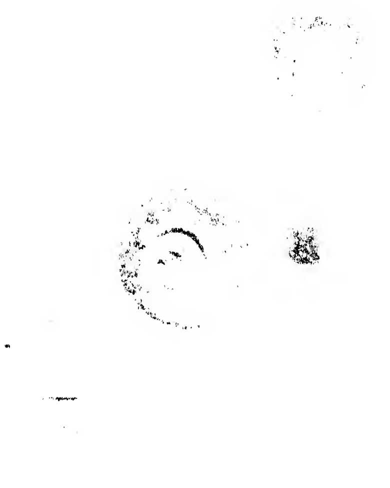


Fig. 1. Automatic Voltage Adjuster
Courtesy of R. E. S. Swam and Co.

As soon as the plant is started up and the voltage brought up to about the right value by operating the hand wheel manually, the wheel is released and the operating motor immediately takes command; if the voltage has not been set exactly correct, the motor will correct it at once and keep it corrected until the plant is shut down.

The setting for the desired line voltage is made by means of a second resistor R-3 on the top of the panel connected to the potential coil.

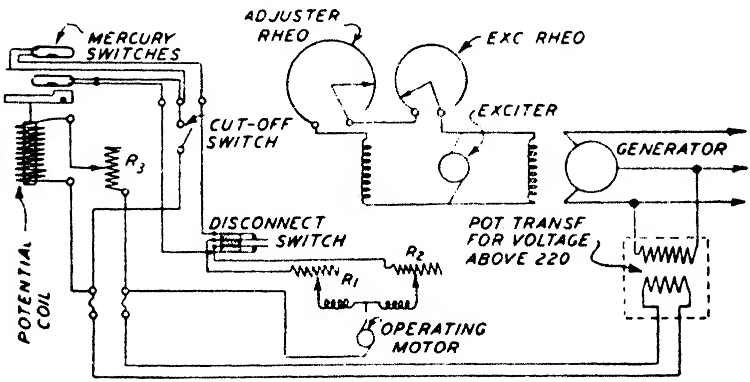


Fig. 2. Wiring Diagram of Swam Automatic Voltage Adjuster

The differential between the voltage above normal and that below normal is made by an adjustment of the angle of the mercury switches with respect to each other.

This adjuster may be used to control two alternating-current generators operating in parallel. In this case a single voltage relay is used to control two motor-driven field rheostats for the respective exciters, and the speed of each motor is independently adjustable.

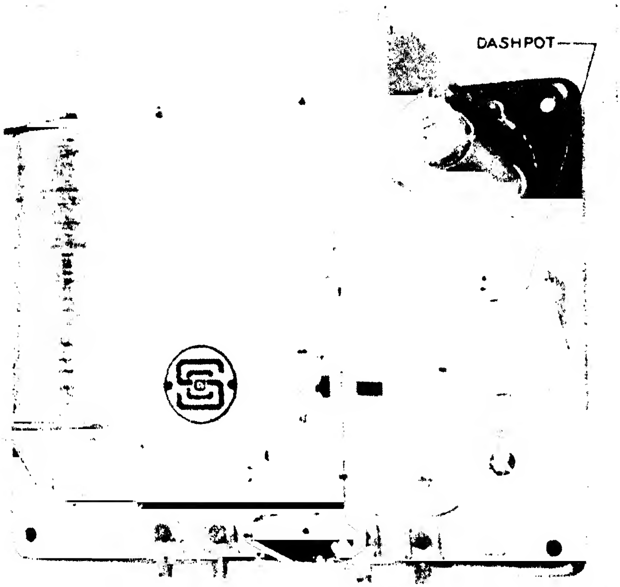


Fig. 8. Carbon-Pile Regulator for Small A.C. Generators

Courtesy of The Safety Car Heating and Lighting Co., Inc.

Circulating currents between the two alternating-current machines must be adjusted to a minimum value by hand control.

Carbon-Pile Regulators. Carbon-pile regulators for alternating-current generators, as in the case of those for direct-current generators previously described, depend on the principle that the resistance of a stack of carbon disks varies according to the pressure applied to the stack. The pressure is automatically varied by means of a potential coil acting through levers. This variable carbon resistor is used to

alter the exciting current of the alternator and thus maintain the alternator voltage constant.

"Three Per Cent" Carbon-Pile Regulators. In Fig. 3 is shown a carbon-pile regulator of The Safety Car Heating and Lighting Company design which is suitable for small alternating-current generators not requiring accurate regulation. This regulator employs a copper-oxide rectifier between the generator terminals and the operating solenoid (shown on the extreme left in Fig. 3) to change the alternating current to direct current, and thus provide a smooth, even pull on the solenoid plunger. The regulation obtained is within plus or minus three per cent.

The pull of the solenoid varies with the current passing through the coil, which in turn depends upon the generator voltage. Variations in the pull of the solenoid produce similar variations in the pressure on the carbon pile by means of a leverage system. It will be seen, therefore, that a variation of line voltage causes a change of resistance in the carbon pile and this change is such as to cause a correction of the generator voltage by varying the field. As the moving parts of the regulator are mechanically balanced, these parts are free to move easily but are not affected by vibration. Overshooting of the moving arm is minimized by an adjustable air dashpot shown at the right in Fig. 3.

The regulator may be connected in the exciter field as shown in Fig. 4, or in some cases may be connected in the generator field as on smaller size generators. The regulators have a voltage rating of 115 volts. Means are provided to allow adjustment of the setting to within 5 per cent either side of the normal rating. External transformers are used to provide for other voltage settings.

As the regulator coil or solenoid heats up, the voltage gradually increases because of the change in resistance of the winding. This effect is reduced by using a temperature control resistance, Fig. 4, whereby the voltage increase is kept down to 5 per cent or less.

"One Per Cent" Carbon-Pile Regulators. For closer regulation the three per cent regulator just described is provided with an additional control panel shown in Fig. 5, instead of the simple copper-oxide rectifier. This control rectifies the current supplied to the coil and so amplifies the changes in coil current produced by departures from normal voltage that regulation is provided within plus or minus one per cent of normal. The wiring diagram is given in Fig. 6. The regulator control panel incorporates a balanced bridge network of

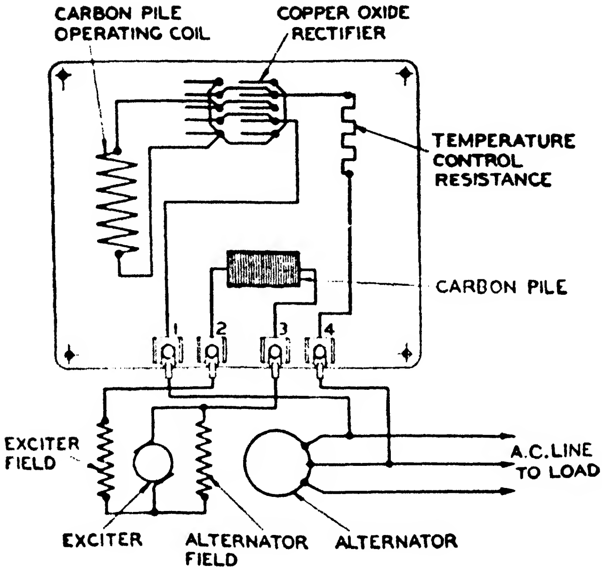


Fig. 4. Wiring Diagram of Regulator Shown in Fig. 3
Courtesy of The Safety Car Heating and Lighting Co.

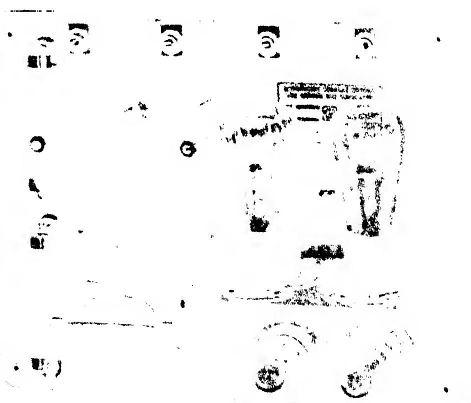


Fig. 5. Control Panel for Obtaining Close Regulation
Courtesy of The Safety Car Heating and Lighting Co., Inc.

resistances and two grid-controlled rectifier tubes. A slight variation of voltage across the network changes the voltages on the grids of the rectifier tubes, causing a comparatively large change of current in the outputs of these electronic tubes, which, in turn, feed the operating solenoid of the carbon-pile panel.

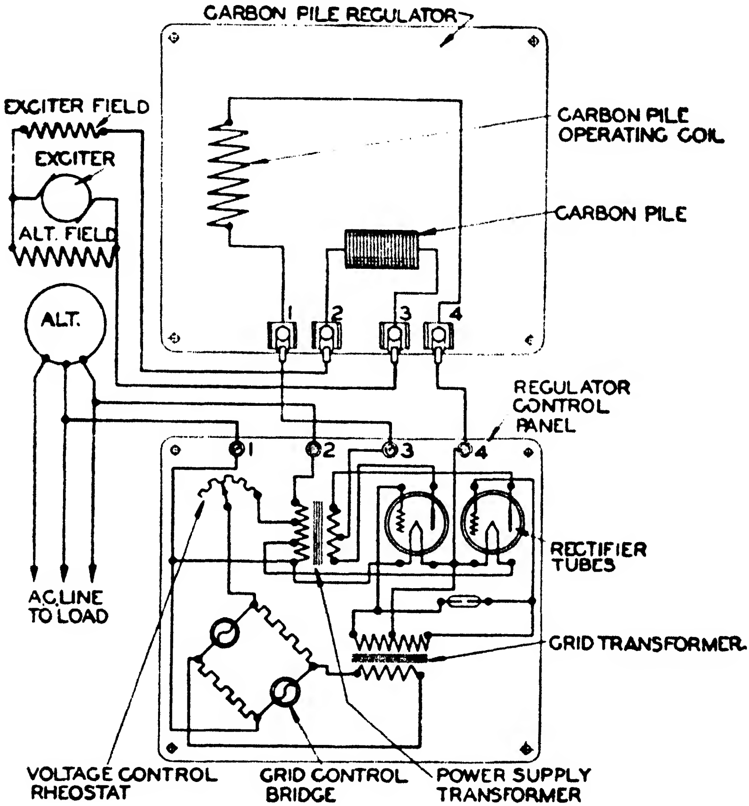


Fig. 6. Wiring Diagram of Control Panel and Carbon-Pile Regulator
Courtesy of The Safety Car Heating and Lighting Co., Inc.

Quick-Acting Rheostatic Voltage Regulators. In recent years, highly refined forms of rheostatic voltage regulators have been developed and have come into general use in applications requiring fast and accurate voltage control. In these regulators the moving parts have little friction and small inertia, so that a small deviation

of the voltage applied to the voltage-sensitive element produces a rapid and large change in the resistance of the rheostatic element. These regulators are sometimes called *direct-acting*, because they employ no relays or vibrating contacts but function by changing *directly* the resistance in the field circuit. They operate only when

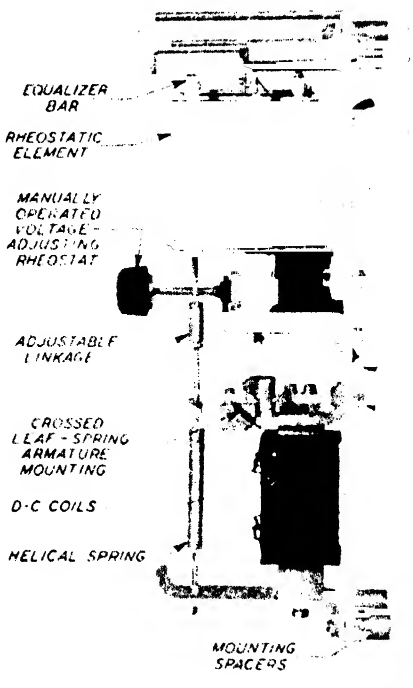


Fig. 7. Side View of "Diactor" Voltage Regulator without Enclosing Case
Courtesy of General Electric Company

a change in excitation is required. Three forms of such regulators are described herewith—the General Electric "Diactor" (Type GDA), the Westinghouse "Silverstat," and the Allis-Chalmers Rocking-Contact Type.

General Electric "Diactor." In this regulator, shown in Fig. 7, the voltage-sensitive element (at the bottom) is a direct-current electromagnet between whose poles is mounted an armature, the pull of

which is balanced against a helical spring. The armature, which is supported by crossed leaf-springs, operates directly a wide-range, quick-acting rheostat consisting of stacks of resistance plates which can be tilted. This rheostatic element is a unique feature. It consists of two or four stacks of resistance plates of special graphitic composition, the stacks being formed, as shown in Fig. 8, from three main parts, namely, resistance plates, a metal contact plate, and an insulating spacer. Each resistance plate has a silver-button insert passing through the plate near the front end. The button is slightly thicker than the resistance plate itself. Insulating spacers separate the resistance plates at the rear of the stack. The metal contact plates located at the center are thicker than either the protruding portion of the silver

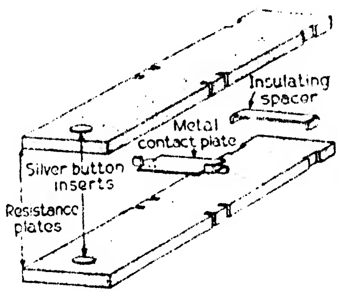


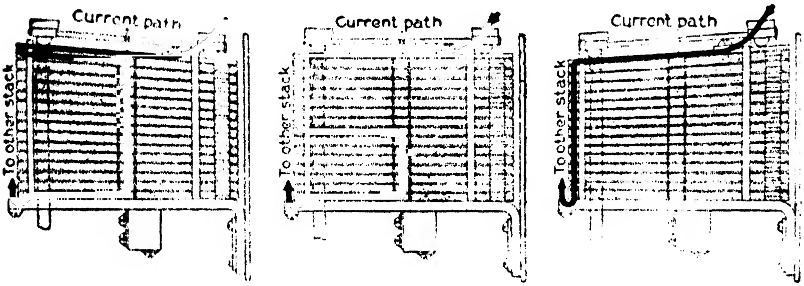
Fig. 8. Parts of "Diactor" Rheostatic Stacks
Courtesy of General Electric Company

buttons or the insulating spacers, and therefore act as fulcrums on which the resistance plates may be tilted. Small fins, protruding from the top and bottom of the metal contact plates, fit into slots cut in the edges of the resistance plates, locking them in position. The metal contact plates also form the electric contacts between the resistance plates, making a resistance path for the current to flow through at the center of the stacks when the rheostat is in the maximum resistance position. It should be noted that there is no electric contact between these metal contact plates themselves, since they are separated by the resistance plates.

The top plate of each stack is made of metal to act as a contact plate for the complete stack. The bottom resistance plate of each stack rests on a copper bracket, which serves as a contact plate and forms a circuit to the adjacent stack. All stacks are connected in series.

Operation consists of a slight motion of the armature, when the voltage deviates, which moves the lever and linkage operating the rheostatic element and tilts the stacks slightly, one way or the other. The manner in which this tilting action changes the resistance is as follows:

When the stacks are tilted back so that the front ends of the plates are separated, the rheostat is in the high or maximum-resistance position, as shown in Fig. 9A. The current path is from the metal contact plate at the top, down through a silver button to the top resistance plate, and then down through the center of the stack through the alternate resistance and metal contact plates. At the bottom of



(A) (B) (C)

A—High-resistance position B—Medium-resistance position C—Low resistance position

Fig. 9. Paths of Current through Rheostatic Stack

Courtesy of General Electric Company

the stack, the current passes from the lowest resistance plate through silver buttons into the copper bracket, which forms the current path to the adjacent stack.

If the stack is gradually tilted forward, its resistance is gradually reduced. This change is caused by a decrease in contact resistance between the resistance and metal plates at the center of the stacks as they tilt forward, combined with the progressive short-circuiting of the plates by the silver inserts (at the front end of the plates) as they come together. Fig. 9B shows the current path through the stack in medium-resistance position after the resistance of the upper part of the stack has been short-circuited by the silver buttons and only the lower resistance plates are effective.

If the tilting action is continued, the resistance is gradually decreased until in the extreme low-resistance position the silver inserts

form a continuous silver path, reducing the resistance to a negligible value. This can be seen in Fig. 9C.

The basic difference between this rheostat and the carbon-pile compression type of rheostat is that the change in resistance is effected entirely by a tilting motion of the stacks, rocking from a metal-to-carbon contact to a silver-to-silver contact, instead of by a change in pressure on the stacks. This tilting action requires only very slight motion and pressure from the operating device, which permits the use of a direct-acting mechanism and high accuracy in the regulator. The silver inserts provide a means for short-circuiting the entire rheostat in the low-resistance position, allowing operation of exciters up to their maximum voltage. All the resistance may be inserted or removed within a few cycles, or the resistance may be varied slowly in an infinite number of steps, depending on the required excitation change. This permits smooth voltage control over the entire range of operation.

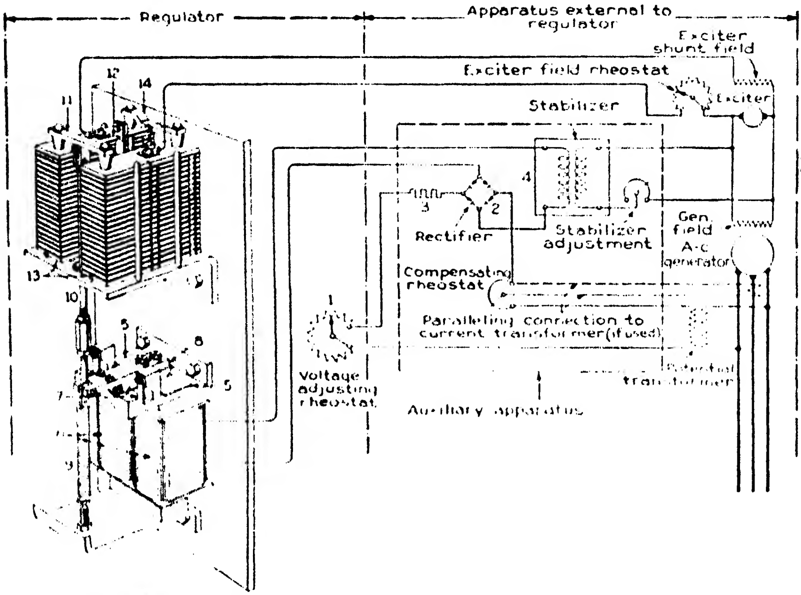
The fact that little pressure is required on the rheostat element permits the use of a very sensitive voltage-control device. If high pressure were required, a large torque element with inherently high inertia and consequently slow operation would be necessary.

Operation. The connections and method of operation of the complete regulator are pictured in Fig. 10. The alternating-current potential is connected through a voltage-adjusting rheostat (*1*) and permanent resistor (*3*) to a rectifier (*2*). The rectifier supplies direct current to the main coils (*6*) of the voltage-sensitive electromagnet. Armature (*8*), trying to align itself with the pole pieces, produces an upward force on the operating rod (*10*), which force is opposed and balanced by spring (*9*). Under normal conditions of alternating-current voltage all forces are balanced, and the armature is stationary.

When a change in voltage occurs, the armature moves to a new position where its force is balanced by the spring, and in doing so it tilts the resistance plates, changing the resistance in the exciter field circuit so as to restore the alternating-current generator voltage to normal.

The purpose of the stabilizer (*4*) is to damp out all undue oscillations and hunting. It will be noted that its primary is connected across the exciter armature and its secondary is in series with the voltage-sensitive coil of the regulator. Its action is as follows: If the exciter voltage is increasing (owing to regulator action caused by a drop in alternating-current voltage), a voltage appears temporarily across the secondary winding of the stabilizer due to transformer

action. This secondary voltage is in the proper direction to add to the voltage obtained from the rectifier, so that the voltage applied to the electromagnet winding is temporarily increased. This action tends to halt the original movement of the rheostatic element, thus preventing overshooting. Upon the exciter voltage becoming constant, no further voltage is introduced into the electromagnet circuit by the transformer



1. Voltage-adjusting rheostat
2. Rectifier
3. Permanent resistor
4. Stabilizer
5. Stator core
6. Main coils
7. Crossed leaf springs
8. Armature
9. Spring
10. Shaft
11. Equalizer bar
12. Lever
13. Rheostatic element
14. Equalizer bar

Fig. 10. Diagram of "Diactor" Voltage Regulator for A.C. Generator

Courtesy of General Electric Company

action of the stabilizer. A similar stabilizing effect is produced when the exciter voltage is being decreased by action of the regulator.

In an earlier model of the General Electric quick-acting rheostatic voltage regulator, an air dashpot was used to provide antihunting action, and a direct-current torque motor opposed by a spiral spring on its shaft was used as the voltage-sensitive element. Another model, known as the G-4 Voltage Adjuster, and intended for inexpensive applications, employed an alternating-current solenoid as the voltage-sensitive element and used a weighted lever to oppose the pull of the solenoid core.

Westinghouse "Silverstat." This type of regulator was described in the preceding chapter in connection with voltage regulation of direct-current generators. For use on alternating-current generators, the fundamental operation is the same, a full-wave Rectox (copper oxide) rectifier being interposed between the voltage-sensitive element

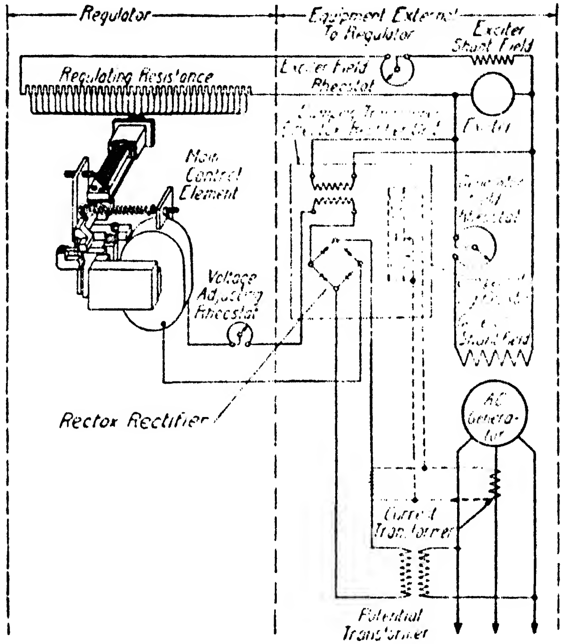


Fig. 11. Diagram of "Silverstat" Voltage Regulator for A.C. Generator. (For Parallel Operation under Control of Individual Regulators, a Current Transformer and Compensating Resistor Are Used for Each Regulator, Connected as Shown by Dashed Lines.)

Courtesy of Westinghouse Electric and Manufacturing Co.

and the alternating-current machine so as to supply the regulator element with rectified direct-current voltage proportional to the alternating-current voltage. A schematic wiring diagram appears in Fig. 11.

Parallel Operation. The foregoing direct-acting regulators, which do not use secondary relays controlled by a master coil (as do many types of voltage regulators), can be used to control only one exciter. In the case of parallel operation of generators, a separate voltage regulator is used to control each exciter, and the exciters are operated

nonparallel. In other words, each generating unit is independent of the others except for the final junction of the generator outputs at the bus bars.

Independent regulation of alternating-current generators has one important advantage in that it can easily be arranged to equalize the power factors of the several generators and thus cause each machine to carry its share of the reactive kilovolt-amperes. When paralleled generators are operating under improper control, it is quite possible to have the engine governors so set that each machine is carrying its correct share of the load, but to have one generator overexcited and the others underexcited. In this case the overexcited generator may carry all of the reactive kilovolt-amperes and thus be overloaded even though the voltage at the bus bars be normal.

To effect automatic control of the reactive current and the voltage, an action called *compensation*, a current transformer and compensating rheostat are added for each regulator. See Figs. 10 and 11. The current transformer is connected in the middle phase with the potential transformer across the two outside phases. The phase relations are then such that the regulator will reduce excitation when its generator produces more reactive current, and vice versa. This action tends to divide reactive kilovolt-amperes between machines in proportion to their ratings and enables the regulators to properly control generators operating in parallel. For the usual range of power-factor, there is not sufficient droop in the voltage caused by the compensation to be noticeable.

Allis-Chalmers Rocking-Contact Type Voltage Regulators. This pioneer quick-acting rheostatic regulator, known as Allis-Chalmers Type A, B, or C, is based on Brown Boveri design and embodies several distinctive features. The regulator is suitable for use in Diesel generating stations where accurate voltage control is required in the face of sudden load variations. The distinctive features are: (a) the use of rocking contact on the rheostat taps, which greatly reduces friction; (b) control device, acting on the principle of an induction motor; and (c) an elastic recall device, consisting of a spring and a magnetic damper, whereby the regulator momentarily overregulates so as to obtain quick action and then immediately assumes a stable position.

The mechanism of this regulator is shown in Fig. 12. The control device is in substance an induction motor used to produce torque instead of rotation. What corresponds to the rotor of an induction

motor is the thin hollow drum of aluminum *C* mounted on a spindle. The torque produced in the drum by the current in the split-phase winding of the stator *E* is counterbalanced by springs *F* and *N*. A sufficiently high resistance is connected in series with the stator winding to prevent variations in temperature and small variations in frequency having any marked effect on the constancy of the voltage which the regulator is set to maintain.

The exciter field rheostat, which is an integral part of the regulator, is built in the form of a commutator. The stationary contacts *L*, to which the taps on the regulating resistor *G* are connected, are concentric with the rotor shaft and are grouped into two or four

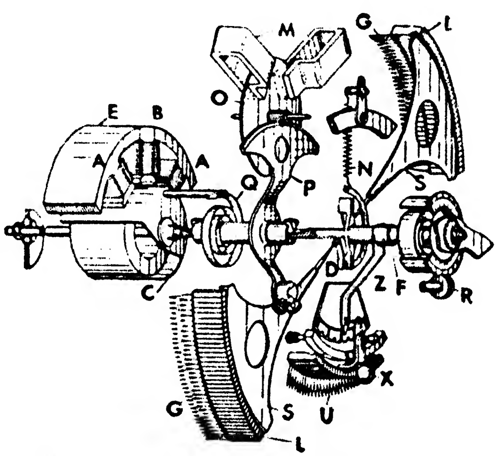


Fig. 12. Mechanism of Allis-Chalmers Rocking-Contact Type Voltage Regulator

commutators, depending upon the size of the regulator. Fig. 13 shows a regulator with four commutators. The inner surface of each commutator, facing the shaft, is heavily silvered and is provided with a V-shaped groove which serves as a guide for its rocking-contact sector S (Fig. 12). The moving sector has a graphite contact surface and is moved by a steel needle point pivoting in a jewel cup. This jewel cup is supported by a leaf spring *D* which is mounted on the rotor shaft. Spring *D* not only presses the contact sector S against the commutator groove, but also serves to transfer every movement of the rotor shaft to the sector by moving its inner end through a small circular arc and causing the sector to roll in the commutator *L*, putting in or cutting

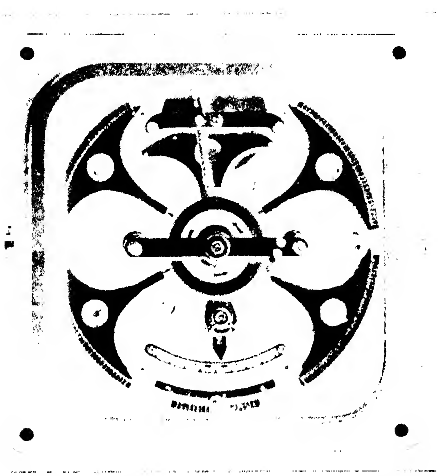


Fig. 13. Four-Sector Rocking-Contact Type Regulator
Courtesy of Allis-Chalmers Manufacturing Co.

out resistance. The latter is connected in series with the shunt field of the exciter, as shown in Fig. 14.

This design of the field rheostat entirely eliminates gliding friction and replaces it by rolling friction which is so small that it can almost be neglected. All moving parts are made of aluminum. Therefore the inertia is small, and as only small displacements are required to cover the whole regulating range, the moving system responds very quickly to changes in voltage.

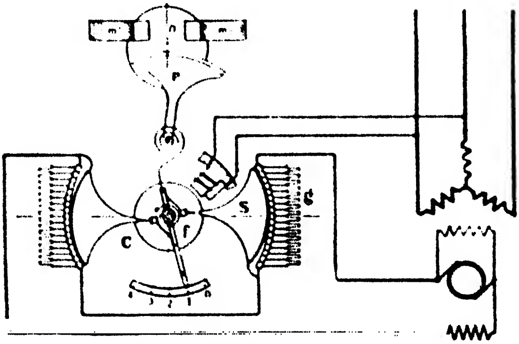


Fig. 14. Wiring Diagram of Rocking-Contact Type Regulator

Because of the light weight and quick action of this regulator, the least drop in voltage causes the rotor to turn quickly into the extreme right-hand position and thus give maximum excitation. This overregulation, if limited to a fraction of a second, is highly desirable since it helps to overcome quickly the magnetic lag in the exciter and the generator field. However, the overregulation must be stopped before the voltage is fully restored, otherwise the regulator would be unstable and would hunt continually from one extreme position to the other. This is accomplished by means of a damping system which consists of an aluminum disk *O*, Fig. 12, rotating between two permanent magnets *M*. The disc is geared to the rack of an aluminum damping sector *P*, which can turn concentrically with the rotor shaft and is fastened to the drum *C* by a spiral spring. Thus the only coupling between the damping system and the motive system (rotor, shaft and sectors) is the spring, called the *recall spring*.

Now as the rotor moves due to voltage change, a tension is produced on the recall spring, since the damping sector *P* cannot follow the rapid movement of the rotor because of the drag of the magnets *M* on the disk *O*. This tension allows the sectors to rock to an overregulating position, but immediately thereafter, under the combined effect of the resulting correction in alternating-current voltage and the tension of the recall spring, the contact sector starts to return. If the recall device has been correctly adjusted to suit the time constant of the alternating-current generator and exciter, the contact sector will come to rest in a new position to give correct excitation for the new alternating-current generator load condition at the same instant that the alternating-current voltage has been restored to normal. The adjustment of the recall device consists of selecting a recall spring of suitable strength and locating the damping magnets *M* at the radius which gives the desired drag on damping disk *O*.

In later designs, the recall spring, instead of being a spiral spring surrounding the main shaft, as shown at *Q* (Fig. 12), is a simple helical spring arranged in a radial position so that it can easily be interchanged.

The method of operation may be summarized as follows: Assuming the generator is fully loaded the contact sectors will take up a position like that shown in Fig. 14, in which a great part of the resistance is short-circuited. This position does not change as long as the voltage remains constant. A drop in load tends to raise the voltage, but the smallest increase is immediately followed by an increase of the

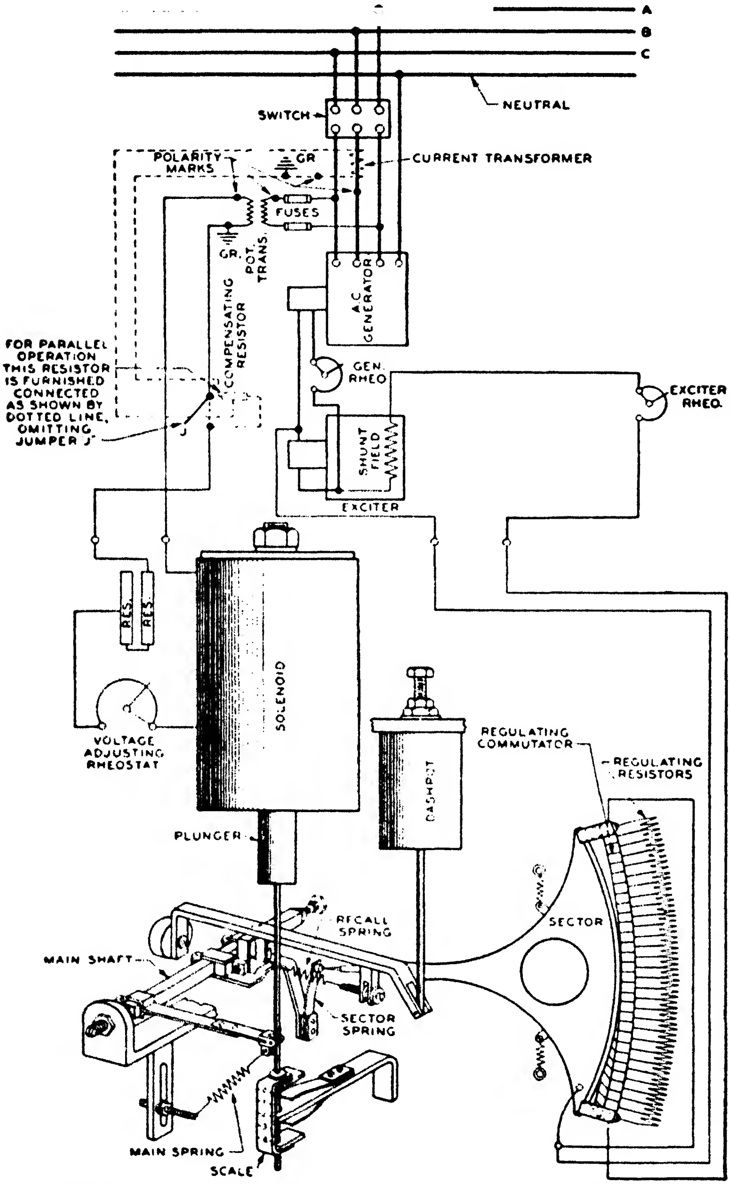


Fig. 15. Construction and Connections of Allis-Chalmers Type V Voltage Regulator for A.C. Generator

Courtesy of Allis-Chalmers Manufacturing Co.

electrical torque so that the system becomes unbalanced. As a result the contact sectors are rocked until the mechanical torque, now increased by the torque of the recall spring, again equals the electrical torque. The resistance inserted in the field circuit by the rocking of the sectors is much in excess of what would be necessary to adjust the excitation to the new load condition. In this way the inherent inertia of the magnetic fields is rapidly overcome and the high voltage is reduced rapidly. The falling voltage, combined with the pull of the recall spring, causes the sectors to start rocking back at once. Meanwhile the damping disk *O* has followed up the motion of the main rotor shaft, thus reducing the tension of the recall spring. The final result is that the contact sectors stabilize in their new position at the same time that the voltage again becomes normal.

There are two independent rheostats in the two-sector type regulator, and four rheostats in the four-sector type. If desired, these rheostats can be connected to different exciters, so that one regulator will control two or four generators simultaneously. However, in such cases, only the plant voltage can be controlled automatically, and the reactive current (wattless current) must be distributed among the parallel-operating alternating-current generators by hand adjustment of the generator rheostats. Furthermore, the magnetic characteristics of the machines must be alike in order that they have the same rate of voltage build-up, otherwise the damping or stabilizing effect of the regulator cannot be adjusted to suit the several generating units.

For these reasons it is desirable to use a separate voltage regulator for each unit. In this case the damping can be adjusted to bring out the best performance of each unit, and reactive current distribution can be made automatic by using current transformers to give cross-current compensation.

Allis-Chalmers also makes somewhat simpler forms of rocking-contact voltage regulators for use in smaller installations. These are known as Type V and are constructed as shown in Fig. 15. The main differences between the Type V and Types A, B, C previously described are:

1. The motive element is a solenoid instead of a torque motor.
2. Damping is effected by an air dashpot instead of by a metal disk revolving between magnets.
3. Only one sector and commutator is used instead of two or four pairs.

VIBRATING TYPE VOLTAGE REGULATORS

Vibrating-contact voltage regulators are made in a vast variety of designs, some exceedingly simple, others quite complicated. The simple types are often used with small high-speed Diesel generating units, whereas the more refined types are especially adapted to central station, municipal, and industrial Diesel generating plants of moderate capacity, and to Diesel power plants for office and apartment buildings. They all operate by varying the strength of the exciter field, which in turn varies the generator excitation and thus the alternating-current voltage.

The principle employed in vibrating regulators is to short-circuit, in a rapidly pulsating manner, a regulating resistor in the exciter field circuit. In other words, the regulator contacts act as a low-resistance shunt across the field resistor, and as the contacts vibrate they simultaneously short-circuit the resistor. The ratio of the length of time the contacts are open to the length of time they are closed is controlled by the voltage-sensitive element of the regulator. This ratio of contact engagement for any short interval of time determines the average or effective resistance in the exciter field circuit during that interval.

Because of the high sensitivity and the lightness of their moving parts, vibrating regulators are able to overregulate momentarily when the voltage changes, and in this manner to reduce the inherent time lag of the generator and exciter. For instance, if the voltage drops, the contacts are, for a while, kept closed longer than normal, thus quickly effecting a large increase in the exciting current. Obviously the overregulation must be only momentary, as otherwise the alternating-current voltage would change too much in the other direction. This would cause the regulator to act again, but in reverse, and would set up a continuous hunting action which of course would be highly objectionable. This hunting action is prevented by stopping the overregulation quickly, thus giving the alternating-current generator voltage a chance to respond before the regulator applies further vigorous measures. Different methods of producing the vibrating and anti-hunting action are employed in the various commercial forms of vibrating regulators.

Vibrating regulators are sensitive to *external* vibration in varying degrees, depending upon the unbalanced weight and the inertia of their sensitive moving parts. Therefore, regulators whose main con-

tacts are operated by the floating cores of solenoids must be so placed and so mounted that they will not be affected by machinery vibrations, tilting, etc. On the other hand, regulators employing a light vibrating armature are little affected by external forces, and some designs may

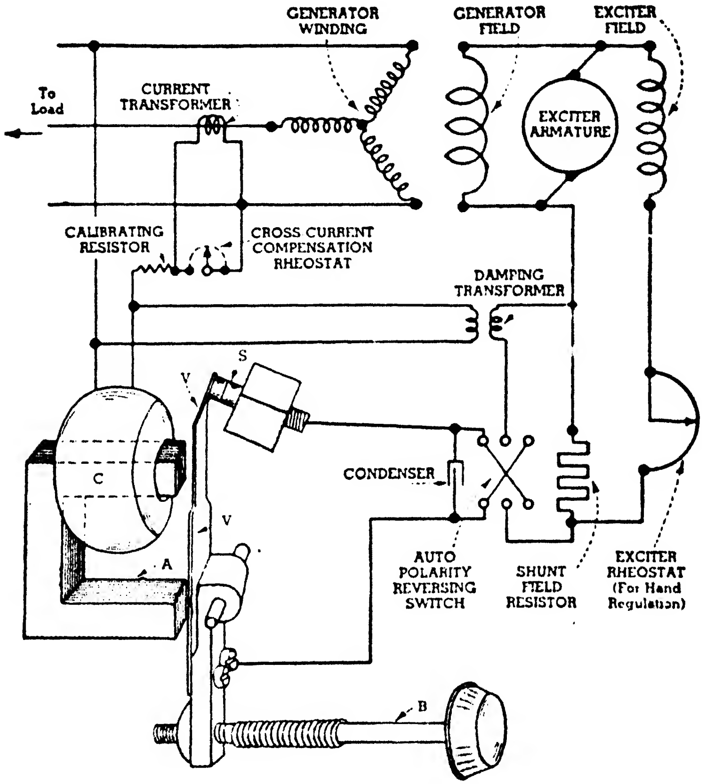


Fig. 16. Construction and Connections of Burlington "Synchrostat" Voltage Regulator for A.C. Generator
Courtesy of Burlington Instrument Corp.

even be mounted directly upon the generator which is being regulated. Such regulators are commonly used on *packaged* units and in portable applications.

"Synchrostat" Voltage Regulators. In the "Synchrostat" voltage regulator, manufactured by Burlington Instrument Corp., the vibrating principle appears in its simplest form. Referring to Fig. 16, the regu-

lator consists of a laminated core *A*, voltage coil *C* and a spring steel vibrator *V*. Vibrator *V* is held under tension by voltage adjusting screw *B*, so that when the voltage coil is not energized, the vibrating contact *V* and the stationary contact *S* are pressed together to short-circuit the exciter shunt field resistor.

Voltage coil *C*, which is connected to the alternating-current generator, sets up a pulsating magnetic flux in core *A* corresponding to each alternation or half-cycle of generator voltage, that is, 120 times per second for 60-cycle frequency. The vibrator, being attracted by this pulsating magnetic force, also pulsates 120 times per second, opening the tungsten contacts each time the voltage wave reaches or exceeds a predetermined positive or negative value. By rapidly clos-

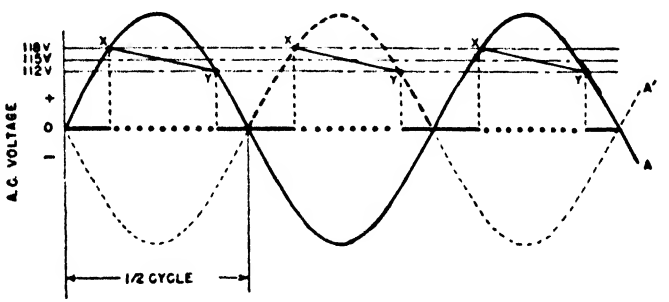


Fig. 17. Diagram Showing Ratio of Contact Engagement of Vibrating Voltage Regulator, for Normal A.C. Voltage

ing and opening the contacts across the field resistor in this manner, a certain average resistance and average exciter voltage is maintained when the alternating-current load is constant.

When the alternating-current load changes and the alternating-current voltage changes with it, the relative time interval the contacts are open or closed is controlled as follows: Referring to Fig. 17, curve *A* represents 1½ cycles of alternating-current voltage. *A′* represents the negative half-cycles revolved into positive half-cycles for ease of explanation, since the vibration of the regulator vibrator is independent of the direction of current in the alternating-current coil. The magnetic pull on the vibrator opens the contacts when the voltage rises to the point *X* on the left of each half-cycle. When the alternating-current voltage decreases to some point *Y* on the right side of the half-cycle, the magnetic pull is low enough to permit the vibrator to be pulled away from the coil by the pull of the spring, and the

contacts are closed. Using the zero-voltage line as a time indicator, it is seen that the heavy sections represent time during which the contacts are closed, and the dotted sections represent the time when the contacts are open.

In Fig. 18 a similar curve shows what happens when the voltage decreases. Points *X* and *Y* remain at the same voltages as before, but there is less of the voltage wave above them. As a result, it will be evident from the diagram that the open period of the contacts has decreased relative to the closed period, and that consequently the average exciter field resistance has been reduced in order to raise the voltage to normal.

It will be noted from Fig. 16 that the voltage coil circuit includes a damping transformer. The function of this transformer is twofold.

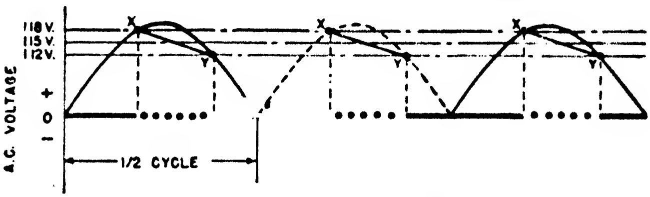


Fig. 18. Diagram Showing Ratio of Contact Engagement of Vibrating Voltage Regulator, for Low A.C. Voltage

First, it stabilizes the regulated voltage (prevents hunting) by increasing the potential on the voltage coil as soon as the exciter field current increases, thus anticipating the subsequent rise of alternating-current voltage after the magnetic lag has elapsed. (This stabilizing action is similar to that previously explained for the General Electric Diactor Regulator.) Second, the transformer increases the regulator action when the excitation is greater. The impulse set up in the primary of the transformer (which is in series with the contacts) when the contacts open is proportional to the magnitude of the current interrupted. The impulse is reflected into the secondary of the transformer and across the regulator coil. The effect of this voltage is to increase the closed period of the contacts with increased exciter current. When low power-factor loads are put on the generating unit, additional exciter field current is required over that required for unity power-factor load. Consequently, improved voltage regulation is obtained with low power-factor loads.

As indicated in Fig. 16, crosscurrent compensation for generators operating in parallel is effected by the common method of using a current transformer and a crosscurrent compensation rheostat in the voltage coil circuit.

A pair of contacts carrying direct-current tend to pit and build up respectively, if the current always passes through them in one direc-

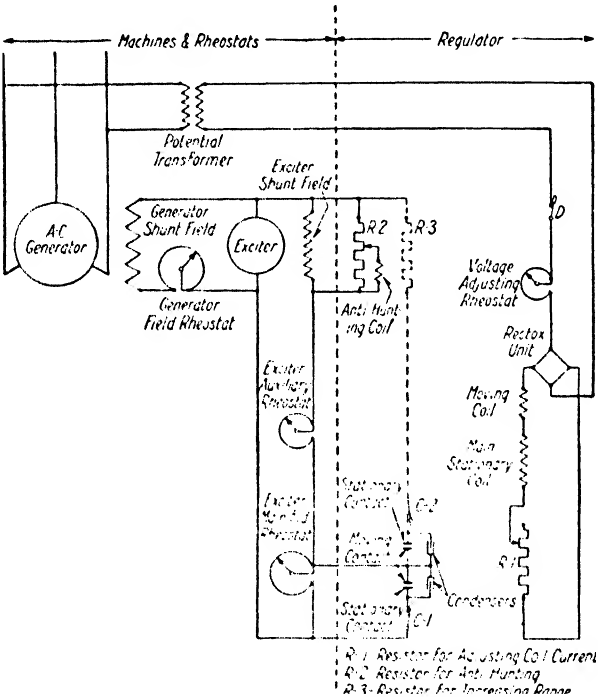


Fig. 19. Schematic Diagram of Westinghouse Type UV-AC Vibrating Voltage Regulator

Courtesy of Westinghouse Electric and Manufacturing Co.

tion. For this reason the polarity of the contacts on vibrating voltage regulators should be reversed daily. On the Synchrostat regulator the polarity is automatically reversed regularly when the regulator is in operation by means of a reversing switch operated by a small motor.

The sensitivity of this regulator is plus or minus two per cent.

Westinghouse Type UV. The fundamental operation of the simple form of vibrating regulator originally developed by the Westinghouse

company for direct-current generators and known as Type UV-DG has already been explained in the preceding chapter. This type of regulator has been adapted for controlling alternating-current generators by adding a rectox rectifier. In this way the control element is actuated by direct current whose voltage is proportional to that of the alternating-current line.

Operation. Referring to the schematic diagram of Type UV-AG regulator, Fig. 19, a drop in alternating-current voltage reduces the direct-current voltage produced by the rectox rectifier and weakens the attraction of the stationary and moving coils, causing contact *C-1* to close. This shunts the exciter main field rheostat and so increases the exciter voltage, which in turn increases the alternating-current generator voltage. But the closing of contact *C-1* simultaneously causes more current to flow through the antihunting coil *R-2* located on the solenoid; this increases the attraction between the stationary and moving coils and causes contact *C-1* to open quickly, thus preventing overshooting of the alternating-current voltage. The process repeats itself rapidly and produces a continuous vibration of the contacts.

Westinghouse Type A. This is an old and well-known type of vibrating regulator for alternating-current generators which employs relays and is sometimes called a *Tirrill* regulator. The vibration is produced by a separate vibrating relay whose contacts cause an interrupting action. The regulator illustrated in Fig. 20 is capable of controlling two exciters. The two upper large coils are the main control magnet and the vibrating magnet, both of which operate the main contacts. Of the three smaller coils below, one is the vibrating magnet relay and the others are the exciter rheostat-shunting relays.

Operation. Referring to Fig. 21, which is a schematic diagram of a regulator with only one rheostat-shunting relay, the main control and vibrating magnets are energized from the alternating-current bus. The cores of both magnets are attracted upward and, in conjunction with the spring and counterweights, actuate the main contacts into and out of engagement. The main contacts, in turn, control the shunting relay or relays.

The shunting contacts alternately open and close across the exciter field rheostat and the effective resistance of the rheostat is determined by the time of contact engagement, which in turn depends upon the alternating-current voltage applied to the main control and vibrating

magnets. For any effective resistance, there is a corresponding exciter voltage and, therefore, alternator voltage.

The vibration is set up by the vibrating magnet relay, which is connected so that the closure of its contacts shunts a small portion of the resistance in series with the vibrating magnet, thus increasing its pull and opening the main contacts. The opening of the main contacts opens all relay contacts and inserts the full resistance in the vibrating

Fig. 20. Westinghouse Type A
Voltage Regulator Panel
Courtesy of Westinghouse Electric and Manufacturing Co.

magnet circuit, weakening the pull and again closing the main contacts. Thus a continuous vibration is set up.

The rheostat-shunting relays and also the vibrating magnet relay are of the differential type, each coil consisting of two windings, one energized continuously and the other intermittently through the action of the main contacts. When one winding is energized, the armature is attracted to the fixed cores against the tension of a spring, thus

opening the contacts. When the differential winding is energized by the closing of the main contacts, it opposes and neutralizes the effect of the first winding, thus allowing the spring to close the contacts. As a result, the contacts of the differential relay are made to vibrate in unison with the main contacts.

Where the number of relays required exceeds the capacity of the main contacts (the usual limit being three, one vibrating and two

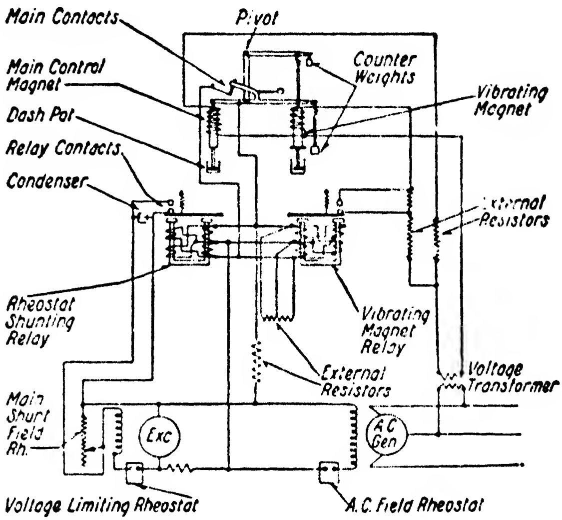


Fig. 21. Schematic Diagram of Westinghouse Type AB Regulator

Courtesy of Westinghouse Electric and Manufacturing Co.

shunting), a master relay is used which makes it possible to actuate as many as eight shunting relays from a single control element. The master relay is also of the differential type similar to the vibrating and shunting relays.

All relays are energized by direct current obtained from one of the exciters, as selected by means of transfer switches.

Reversing switches are connected in the leads from the various relay contacts. Their purpose is to reverse the polarity across the contacts and thus minimize any tendency for one contact to build up. The single-pole disconnecting switches below the reversing switches are connected only in the shunting-contact leads and serve to disconnect the regulator from the machine which it is controlling.

The distinctive features of this type of vibrating regulator are as follows:

1. Quick action.
2. Ability to force the field to the limit and hold it there indefinitely if necessary.
3. Multiple-unit control, making it possible to control a number of units simultaneously from a single regulator.
4. Individual shunting relays, making it possible to provide for unanticipated future machines by the addition of extra relays, within the limits of the regulator.

The rated sensitivity of this regulator is within plus or minus 0.5 per cent.

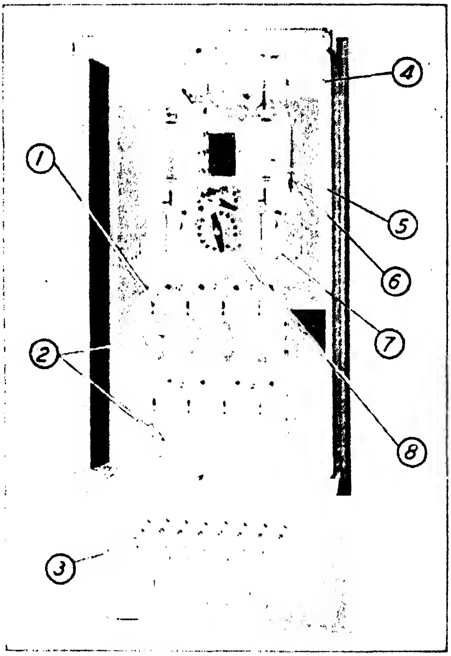


Fig. 22. Westinghouse Vibrating Type Voltage Regulator

Courtesy of Westinghouse Electric and Manufacturing Co.

(1) Relay contacts are of two kinds as follows: For *V* and *X* relays an especially durable contact material is used. For shunting relays, because of the greater wear and more frequent renewal required, silver is the standard material, but tungsten is available in special cases where preferred.

(2) The number of shunting (*S*) relays depends on the number and size of machines controlled. One vibrating (*V*) relay required to force and maintain vibration in a manner dependent only on the regulated A.C. voltage. When more than three shunting relays are required on one regulator, one or more master (*X*) relays are used. These are connected between the main contacts and the shunting relays to relieve the main contacts of unnecessarily heavy duty.

(3) Reversing switches are provided for periodically reversing the polarity of *M*, *X* and *S* contacts, thus prolonging the time between maintenance periods.

(4) Main contacts (*M*) operated by the control coils which maintain a continuous vibrating action, part time open and part time closed. This vibrating action energizes the relays and causes them to vibrate continuously.

(5) Coils of control element are energized from the bus voltage through a potential transformer.

(6) Regulating counterweights by which the regulated voltage may be adjusted at installation to a value between the taps on the external resistor as required.

(7) Dashpots with ports adjustable by needle valves. These dashpots permit installation adjustment so that the damping characteristics of the control element match the machine and load characteristics.

(8) The compensating dial switch with which the control element is biased for crosscurrent or line-drop compensation as required by the particular installation.

The various parts of this regulator, with their functions indicated, are shown in Fig. 22.

General Electric Type TA. Like the Westinghouse Type A, this is also a well-known type of regulator for alternating-current generators, operating on the principle of rapidly opening and closing a shunt circuit across the exciter field rheostat. It differs, however, in

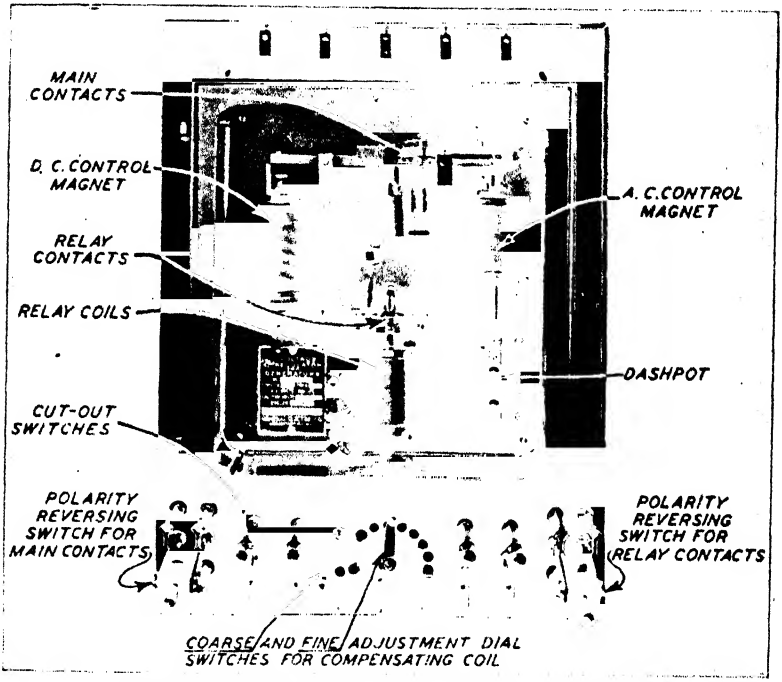


Fig. 23. General Electric Type TA Voltage Regulator for Controlling One Exciter

Courtesy of General Electric Company

that the vibration is produced entirely by the direct-current circuit, and that the voltage-sensitive element comprises both alternating-current and direct-current control magnets. The main contacts float, i.e., *both* contacts are movable, one being controlled by the direct-current exciter voltage and the other by the alternating-current generator voltage.

A view of this regulator, with the various components indicated, is given in Fig. 23. The form shown contains a single shunting relay

and is suitable for controlling one exciter. Fig. 24 is an elementary diagram of the connections.

Operation. The regulator consists fundamentally of two parts, a direct-current control system and an alternating-current control system which cooperate in determining the position and movement of the main (floating) contacts. The direct-current control system is simply a direct-current regulator having a main control magnet and relay magnet connected across the exciter mains, the contacts of the relay being arranged to shunt the exciter field rheostat. This operation

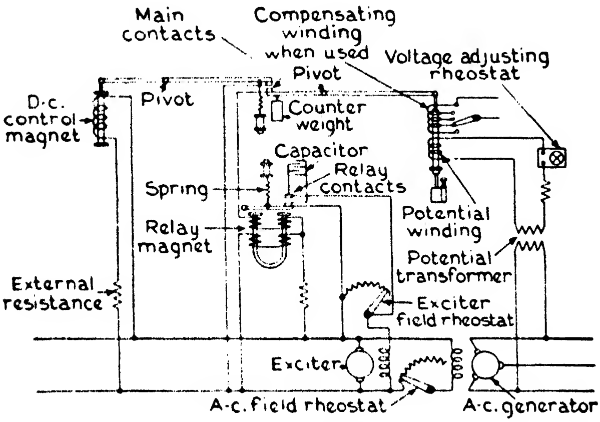


Fig. 24. Elementary Diagram of General Electric Type TA Voltage Regulator

Courtesy of General Electric Company

maintains not a constant but a varying exciter voltage, the value varying in accordance with the demands of the alternating-current control magnet which is connected to the alternating-current bus, the latter magnet being the alternating-current portion of the regulator.

The direct-current control magnet is responsive to exciter voltage and attracts downward a movable core attached to a pivoted lever, at the other end of which is a flexible contact. This is one of the floating main contacts. A differentially wound relay magnet is also connected to the exciter bus, one winding being permanently connected to the bus, while the other is arranged to be opened and closed by the floating main contacts. The relay contacts are connected across the exciter field rheostat.

The potential winding of the alternating-current control magnet is connected across the generator bus through a potential transformer. This magnet is of the ordinary solenoid type, having a laminated iron core which is attracted upward by the magnetizing force. The core is attached to a pivoted lever, at the opposite end of which is mounted the lower main (floating) contact.

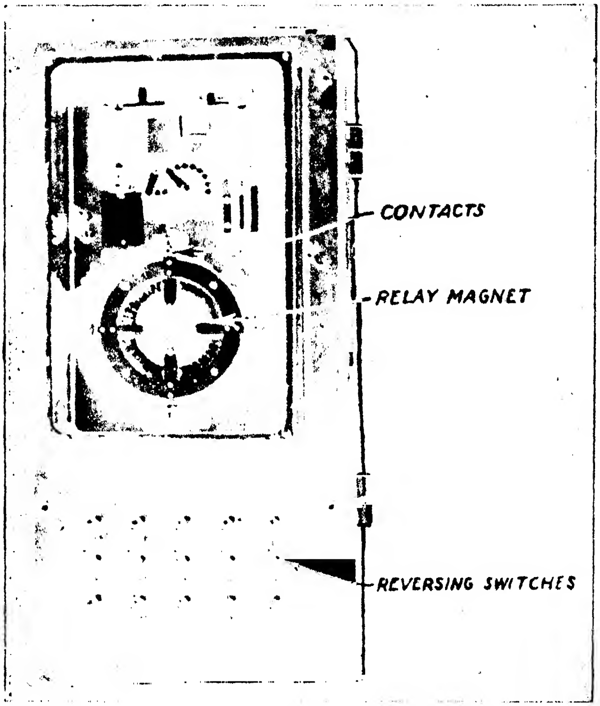


Fig. 25. General Electric Type TA Voltage Regulator for Controlling Several Generators
Courtesy of General Electric Company

It will be seen from the foregoing that the exciter voltage is controlled by the rapid opening and closing of the relay contacts. The value of the voltage depends upon the position of the alternating-current magnet core and lever arm, which is in turn dependent upon the value of the alternating voltage being held.

At any constant load, speed, and power-factor, the alternating-current magnet core does not actually move, the regulator acting as

a direct-current regulator maintaining the proper exciter voltage to give the correct alternating voltage. Should the power-factor change, or should a heavy load be thrown upon the alternator, the previous exciter voltage will not give the correct alternating voltage. Therefore the alternating-current core will drop slightly. This forces the lower main contact against the upper main contacts, which in turn closes the relay contacts. This, as previously explained, causes the exciter voltage to increase. The travel of the alternating-current magnet core will continue until the exciter voltage has reached a value corresponding to that required to give normal alternating voltage under the new conditions. The direct-current side of the regulator will then operate and maintain the exciter voltage of the regulator at this higher value in order to hold again the proper alternating voltage. In case the load drops on the alternating-current generator, the reverse action takes place and the regulator maintains a lower exciter voltage, in order to give the correct alternating voltage.

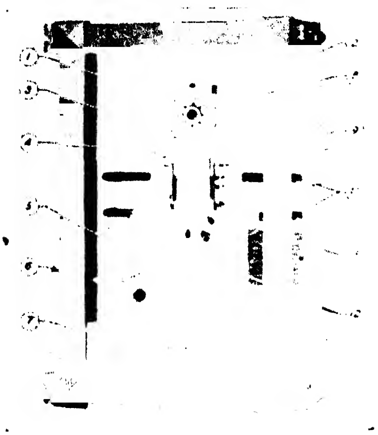
This regulator can also be arranged to control more than one exciter, the principle of operation being the same except that several shunting relays are used instead of one. The regulator appearance is then as shown in Fig. 25.

COMBINATION RHEOSTATIC-VIBRATING VOLTAGE REGULATORS

Automatic control of voltage on large alternating-current machines frequently involves field currents and rheostat capacities beyond the practical range of application of either the direct-acting rheostatic or vibrating-contact types of regulators. The indirect-acting rheostatic type regulator, which uses a combination of rheostat movement and vibrating contacts, is especially adapted to large central station installations where large, slow-speed exciters are used or where the rate of response to change in voltage on the field of the generator is slow. This type of regulator is adapted to three-phase instead of single-phase response and avoids the operating difficulties encountered with the continuously vibrating contacts of vibrating regulators when used for heavy field currents. In this regulator no motion occurs until there is a change in voltage. Then a combination of vibrating relay contact action and rheostatic regulation corrects conditions until the rheostat reaches the correct position for the new load condition.

The indirect-acting regulator with its accompanying high-speed relays and motor-operated exciter field rheostat is relatively expensive,

and its use is usually limited to the control of large and important machines. Two forms of this type of regulator are briefly described herewith.



1. Notching contact wheel (1) constantly driven by contact motor
2. Accelerating contact wheel (2) constantly driven by contact motor
3. Raising accelerating contact (R_2) controlling high-speed relays
4. Raising notching contact (R_1) controlling motor-operated exciter field rheostat
5. Adjusting balancing spring
6. Enclosed case. Glass is easily removed for accessibility to regulator parts
7. Magnetic damping device
8. Lowering notching contact (L_1) controlling motor-operated exciter field rheostat
9. Lowering accelerating contact (L_2) controlling high-speed relays
10. Square studs prevent turning when making connections
11. Lever arm connected to shaft of 3-phase torque-motor voltage-sensitive element
12. Main contact arm travel-limit stops

Fig. 26. Main Control Element, General Electric Type GFA-4 Indirect-Acting Voltage Regulator, Front View

Courtesy of General Electric Company

1. Contact motor constantly driving notching and accelerating contacts at four r.p.m.
2. Studs for mounting regulator on switchboard panel
3. Brush carrying current to notching and accelerating contact wheels (1) and (2)
4. Notching contact wheel (1) constantly driven by contact motor
5. Accelerating contact wheel (2) constantly driven by contact motor
6. Magnetic damping device requires no maintenance
7. Voltage-sensitive element consisting of 3-phase torque motor mechanically connected to main contacts. Torque motor averages 3-phase voltages
8. Regulator mounted on small metallic base for permanent mounting on switchboard

Fig. 27. Main Control Element, General Electric Type GFA-4 Indirect-Acting Voltage Regulator, Side View

Courtesy of General Electric Company

General Electric. The main components of this regulator, known as Indirect-Acting Type GFA-4, are a main control element shown in Figs. 26 and 27, with a motor-operated exciter field rheostat, and a relay panel with high-speed relays. The voltage-sensitive part of the main control element, which is the heart of the regulator, is a poly-

phase torque motor responsive to the average voltage of all three phases. A rotating cam contact wheel is used which gives the desired intermittent contact action without depending upon the direct-current interrupter action that is employed in the vibrating-contact types of regulators.

Two sets of contacts provide for separate operation of the exciter field rheostat for small changes, and of the high-speed accelerating relays for large changes. For small changes of voltage the first set of contacts functions by moving the motor-operated field rheostat to a new position, but as the engagement of the contacts is interrupted by the rotating cam, the rheostat is moved in short steps allowing sufficient time for the alternating-current voltage to be corrected between steps. The greater the voltage change, the longer the time of engagement and the faster the motion of the field rheostat. If the voltage change is large enough, the second set of contacts comes into action. These operate the accelerating relays which cut in or out *all* of the regulating resistance. The regulator acts rapidly when the maximum rate of voltage correction is needed, the time required to close the accelerating contacts and to operate the accelerating relays being only 3 cycles or $\frac{1}{20}$ of a second. When the voltage is steady, the regulator contacts do not close at all. In this regulator the control is effected through varying the resistance in the exciter field circuit and therefore the exciter armature voltage is nonuniform. An individual regulator is required for each alternating-current machine to be controlled, and each alternating-current machine must have its own individual exciter.

Westinghouse. The Westinghouse company also builds a combination type of regulator known as Indirect-Acting Exciter Rheostatic Type BJ. This operates similarly to the General Electric type just described. The control element, however, consists of a solenoid coil which is energized by a direct-current voltage that is rectified from the three-phase alternating-current source being regulated.

The rheostat is notched step by step to its correct position when normal alternating voltage has been closely approached, or when the load change is very slight. However, this does not appreciably affect the rate at which voltage restorations are made, since the notching process does not start until the alternating voltage has been restored to within a few per cent of its normal value.

Under steady load conditions the regulator is in a state of rest, operating only when the necessity arises.

ELECTRONIC-TYPE VOLTAGE REGULATORS

Electronic-type voltage regulators differ fundamentally from the rheostatic and vibrating-contact types previously described. The electronic type regulator itself is the *source* of the current for the exciter field, whereas in the other types the current for the exciter field is

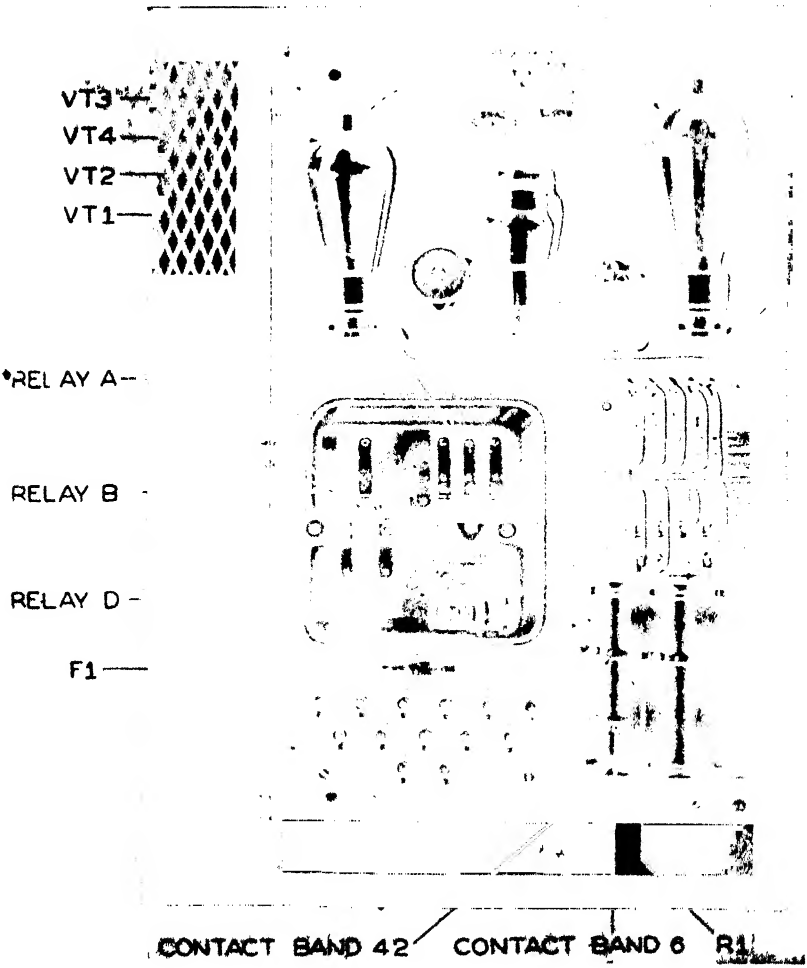


Fig 28 Ward Leonard Type EF Electronic Voltage Regulator with Cover Open
Courtesy of Ward Leonard Electric Co

produced by the exciter armature and is merely *controlled* by the regulator. The electronic type also differs from the others in that instead of using mechanical control mechanisms, a stream of electrons having no inertia and no time lag provides the regulatory action. The advantage of having the regulator itself produce the exciter field current is that the rate of alternating-current voltage response is increased because the exciter field potential is not limited by the exciter armature voltage.

Ward Leonard Electronic Regulator. The Type EF Regulator built by the Ward Leonard Electric Company, which is one of the best known electronic types, is shown with cover opened in Fig. 28. The four electronic tubes used, *VT-1, VT-2, VT-3, VT-4,* are respectively: a -01A tube which is the voltage-sensitive element, a -47 tube to amplify the detections, a grid-controlled rectifier tube, and a plain rectifier tube. Relays *A, B* and *D* under the glass cover are protective devices; contact bands *42* and *6* on the cylindrical resistor are used to adjust the antihunt action.

Fig. 29 shows the elements of the circuit used, omitting the protective and antihunting features. Tubes *VT-3* and *VT-4* constitute a full wave rectifier, supplied with alternating-current power through a transformer and delivering its direct-current output to the field of the exciter. One of these tubes is grid-controlled and thus adjusts the output of both rectifier tubes because of the electromagnetic coupling provided by the high inductance of their common load, the exciter field-winding. The grid bias on the grid-controlled tube *VT-3* is controlled, through the grid transformer, by the amount of plate (anode) output of amplifier tube *VT-2.* (This tube and the condenser shown constitute a phase-shifting circuit.) The plate output of amplifier tube *VT-2* is controlled, in turn, through the amount of negative bias voltage applied to its own grid by the voltage drop in resistor *R-1.* This voltage drop is proportional to the current flowing in resistor *R-1,* which in turn depends upon the plate output of tube *VT-1,* the voltage-sensitive element of the regulator.

To understand the voltage-sensitive action of tube *VT-1* it should be explained that the electron emission of a high-vacuum tube varies with the temperature of the cathode (filament). If the anode (plate) voltage is set high enough, so that *all* of the electrons emitted by the heated cathode are attracted to the anode, then the maximum possible current will flow in the anode circuit, and the current will vary with the cathode temperature. This is known as operating at plate saturation.

This principle is utilized to change the anode current of *VT-1* in accordance with changes in the alternating-current generator voltage. The cathode of *VT-1* is energized, through the control transformer, from the alternating-current voltage to be regulated. Consequently, any change in alternating-current voltage immediately changes the

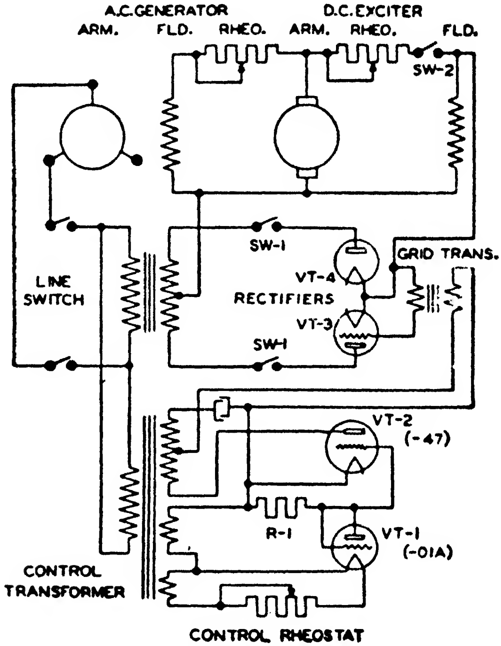


Fig. 29. Elementary Circuit Diagram, Ward Leonard Type EF Electronic Voltage Regulator
Courtesy of Ward Leonard Electric Co.

temperature of the thin filament of *VT-1* and in turn changes its anode current.

Referring to Fig. 29, this regulating cycle may be briefly summarized as follows:

1. Assume the alternating-current generator load decreases and the alternating-current voltage starts to rise.
2. The voltage and temperature of the cathode of *VT-1* increase.
3. The anode current of *VT-1* increases and the drop across the resistor *R-1* increases.
4. The negative bias voltage on the grid of *VT-2*, which is the

voltage drop across *R-1*, increases and reduces the plate current of *VT-2*, thereby increasing its resistance.

5. The phase of the grid voltage applied to *VT-3* is altered in a direction to decrease the output of both *VT-3* and *VT-4*.
6. The shunt field current of the exciter is reduced, the alternating-current generator voltage is lowered and the system comes back to normal.

"Field forcing" (previously explained) is a basic feature of the Type EF regulator. If necessary, the regulator may apply as much as 160 volts for a few instants to the field of a 125-volt exciter. The sensitivity is plus or minus one per cent, and the regulator acts one-half cycle ($1/_{120}$ second) after any change in alternating-current voltage. For sudden load changes up to 50 per cent of rated generator kva, voltage is restored to normal band within $1\frac{1}{2}$ seconds, provided the Diesel speed droop is kept within 5 per cent and the time constant of the exciter-generator combination does not exceed 3 seconds.

Automatic protective devices cut out the regulator and return the generator to hand control in case of tube failure or short-circuit; protect the regulator itself against excessive alternating-current voltage; and protect the insulation of the exciter field winding when the field current is rapidly reduced.

One important precaution which must be observed in using this regulator is to allow fully five minutes' time to elapse to heat up the rectifier tubes before putting the regulator in control.

PARALLEL OPERATION

Two or more electric generators are said to be operating in parallel when the machines are electrically connected, or, in other words, when they are delivering current to the same set of bus bars. Parallel operation permits wide flexibility in loading of generators and effects many economies. Most Diesel electric plants containing more than one unit are arranged for parallel operation.

DIRECT-CURRENT GENERATORS

Shunt-Wound Generators. A simple example of paralleling direct-current machines is shown in Fig. 1, which illustrates the case of two shunt-wound generators, *A* and *B*. The voltmeter *V*, by means of a double-throw switch, can be made to indicate the terminal voltage of either machine *A* or *B*. Assume generator *A* is in service and connected to the busses, its main switches being closed. To parallel generator *B* with generator *A*, *B* is brought up to speed and its field

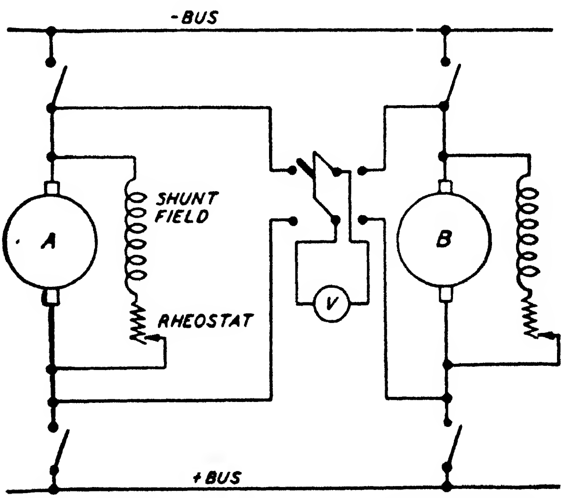


Fig. 1. Diagram of Connections for Parallel Operation of Two Shunt Generators

rheostat adjusted until the terminal voltage of *B* is the same as that of *A*. *B*'s main switches are then closed, putting *B* in parallel with *A*. However, *A* will still carry all of the load, and *B* will run idle until the voltage of *B* is further increased by means of its field rheostat, whereupon *B* can be given any desired part of the load. Since the voltage of shunt-wound generators drops off with increase of load, it is evident that when a certain load is divided between the generators in a certain ratio, that ratio will be automatically maintained as long as the load remains the same. If, for example, because of a momentary speed change, generator *A* should start to take more than its share of the load, the terminal voltage of *A* would start to fall and would cause *A* to relinquish the additional load at once.

If the shunt-wound machines have similar voltage characteristics, i.e., if the same increase in load will cause the same drop in voltage on both machines, they will divide the load in the same ratio regardless of variations in the total load. If their voltage characteristics are not the same, some regulation of the field rheostats may be required when a change in load takes place.

Compound-Wound Generators. The paralleling of compound-wound generators is not as simple as that of shunt-wound machines because of the effect of the series fields. The latter have a marked effect on the voltage characteristics, tending to cause the terminal voltage to rise with increase of load instead of falling, as in the case of shunt-wound machines. Thus, if two (or more) compound-wound generators were to be connected in the simple manner of shunt-wound, the division of load would be unstable. If one machine should start to take more than its share of the load, its series field would be strengthened and its terminal voltage would increase. This, in turn, would cause the same generator to assume still more of the load, whereupon its voltage would increase further. The effect would be rapidly cumulative and would finally result in the one machine not only carrying all of the load but also operating the other generator as a motor. For this reason, it is necessary to use an *equalizer connection* with all compound-wound generators operating in parallel.

The purpose of the equalizer connection is to place the series fields in parallel so that any tendency of one armature to increase or decrease its load will automatically increase or decrease the load on the other armature. The equalizer connection should be of low resistance and should be located as shown in Fig. 2. Since the current flowing through each series coil is proportional to its resistance and is inde-

pendent of the load on any one machine, an increase of voltage on one machine builds up the voltage of the other at the same time, so that the first machine cannot take all the load but will continue to share it in proper proportion with the other generator (or generators).

Compound-wound generators should first be adjusted to operate stably in parallel as shunt generators, that is, without the series fields, by proper brush setting. After that, the series fields may be adjusted by resistances or shunts so that the same full-load voltage is obtained on all machines and the load will divide properly at all intermediate loads.

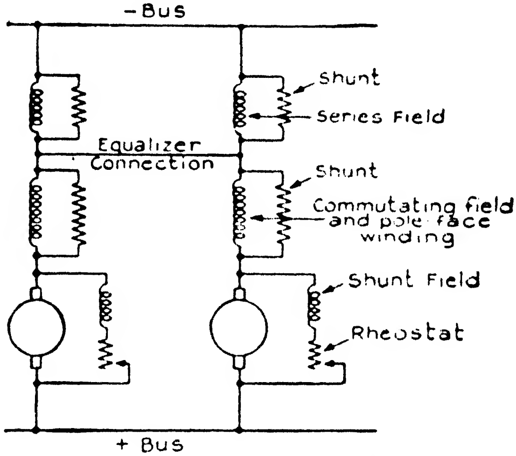


Fig. 2. Connections for Parallel Operation of Two Compound-wound Generators

To obtain proper division of load between generators, the voltage characteristics, when plotted against per cent load, should be the same, or very nearly so. In determining the voltage characteristics, the change in speed of the Diesel engine with load should be taken into consideration.

The shape of the voltage characteristic is dependent upon the type of generator, design, and adjustment. The amount of droop in the case of shunt generators can be changed somewhat by shifting the brushes or changing the strength of the commutating poles. However, the range of adjustment by these methods is limited by commutation. The voltage regulation of a compound generator may be changed by varying the strength of the series field.

From the point of view of good parallel operation, it is much better to have all generators flat compounded or even with a voltage characteristic that droops slightly with load.

Actual connection diagrams for generators operating in parallel are more elaborate than the simplified diagrams in Figs. 1 and 2. The Westinghouse plan for connecting a 3-wire commutating pole 125–

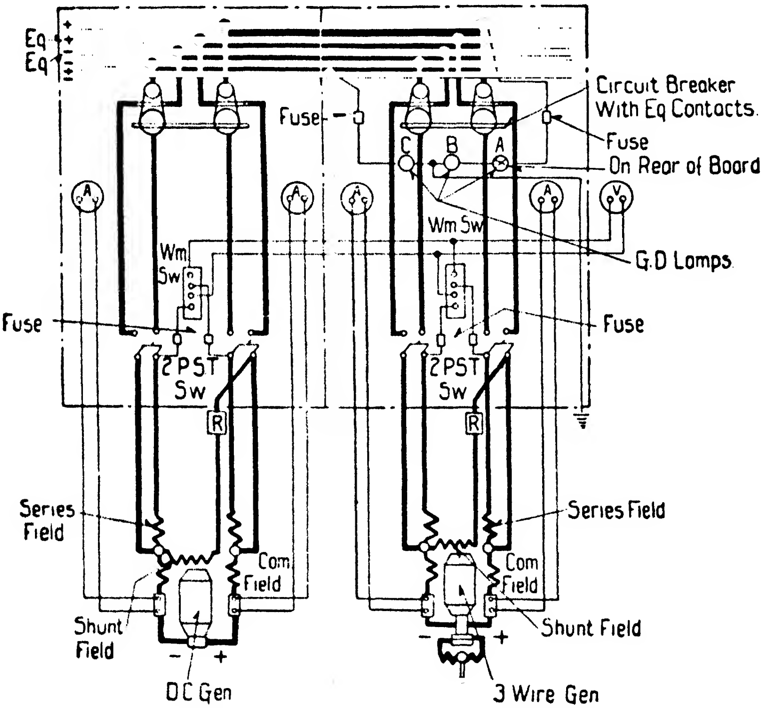


Fig. 3. Diagram of Connections for Paralleling a Three-Wire 125–250-Volt D.C. Generator with a Two-Wire 240-Volt Generator

Courtesy of Westinghouse Electric and Manufacturing Co.

250-volt compound-wound generator with a 2-wire 240-volt generator is shown in Fig. 3.

Direct-Current Generators Equipped with Voltage Regulators. For satisfactory parallel operation of direct-current generators under the control of individual voltage regulators, it is necessary to make provision for the proper division of the kilowatt load between the generators. This is accomplished by means of compensation between the

regulators, which is obtained by the addition of a compensating winding to the main regulating winding on each regulator. The compensating windings are energized by the drops across the commutating or series fields of the direct-current generators, or from shunts when such fields are not available. An adjustable resistor is used to adjust

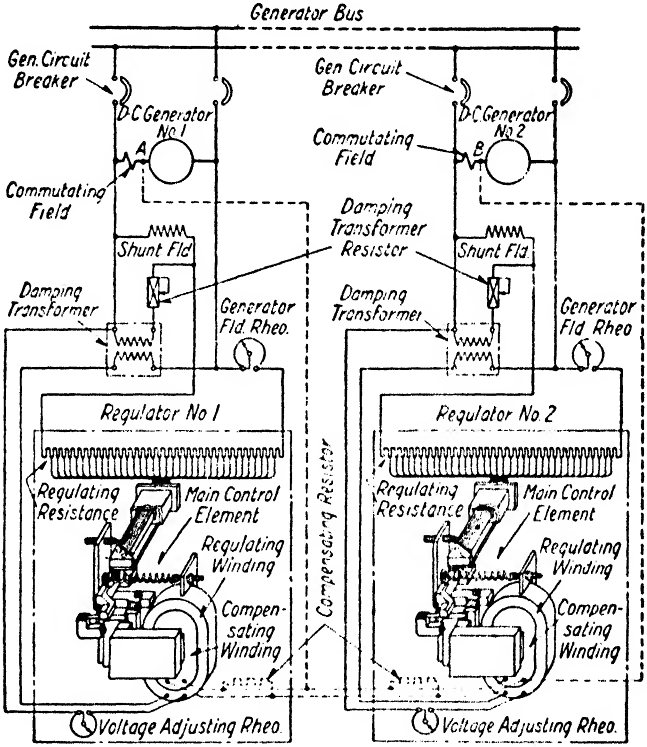


Fig. 4. Diagram Showing Compensating Windings on Voltage Regulators Controlling Two Paralleled D.C. Generators
Courtesy of Westinghouse Electric and Manufacturing Co.

the compensation as required by the characteristics of the individual generators.

Referring to Fig. 4, drawn specifically for Westinghouse "Silverstat" regulators, the compensating windings on the two regulators are cross-connected in parallel, which causes the two windings to have an opposite effect with respect to a given direction of current flowing through

them. Thus, a current flow introduced into this circuit in a given direction will, in one case, cause the compensating winding to aid the main regulating winding and, in the other case, oppose it.

The commutating fields on the two paralleled direct-current generators are in series with their connections to the two compensating windings, points *A* and *B*, Fig. 4. If generator *No. 1* takes more than its share of the load, the increased current will create a greater voltage drop through its commutating field, causing a voltage difference between points *A* and *B*, which in turn causes current to flow through

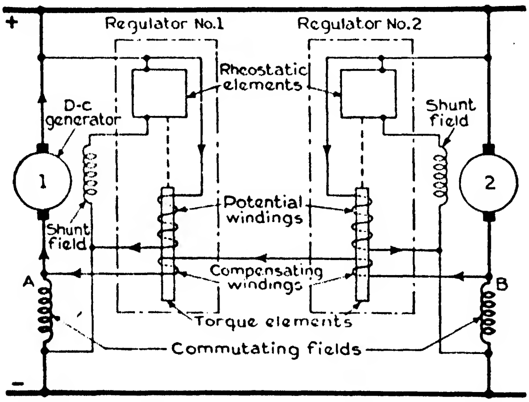


Fig. 5. Schematic Connection Diagram of Regulators Controlling Two Paralleled D.C. Generators. (Showing direction of momentary current flow in compensating windings if generator No. 1 takes more than its share of load.)

Courtesy of General Electric Company

the circuit of the compensating windings. The direction of this current is such as to cause compensating winding on regulator *No. 1* to aid the pull of the main regulating winding on that regulator, to cause the regulator to cut in field resistance, and to lower the voltage on generator *No. 1*. At the same time compensating winding on regulator *No. 2* opposes pull of the main regulating winding on that regulator, causing the regulator to cut out field resistance and raise the voltage on generator *No. 2*. The foregoing action causes the load to be shifted from generator *No. 1* to generator *No. 2* until the load is again properly divided.

It will be seen that the compensating action functions to produce the same result as an equalizer bus connection that is used for dividing the load on paralleled compound-wound direct-current generators under manual control. Hence, when individually compensated regulators are used, an equalizer bus is neither required nor used.

The same scheme of adding a compensating winding to the main regulating winding (i.e., the voltage-sensitive element) is employed when General Electric "Diactor" regulators are used to control direct-current generators operating in parallel. Fig. 5 shows the schematic connection diagram and indicates the direction of momentary current flow in the compensating windings if generator 1 takes more than its share of load. For the sake of simplicity, this diagram does not show the stabilizing winding on the voltage-responsive electromagnet of the General Electric Diactor regulator. Actually, there are three windings, each with an independent function:

1. The potential winding, which indicates the generator voltage.
2. The stabilizing (or damping) winding, which prevents overshooting and hunting.
3. The compensating winding, which equalizes the loads carried by paralleled generators.

ALTERNATING-CURRENT GENERATORS

The process of paralleling alternating-current generators involves more steps than the paralleling of direct-current machines. In the case of direct current, the equalization of voltage between the incoming machine and the line is the important factor. In the case of alternating current it is not only necessary to bring the generators to the same voltage, but they must be of the same frequency and, most important of all, exactly in phase. In the case of alternating-current machinery, the process of paralleling is generally termed *synchronizing* because of the dominating importance of the two currents being in phase or in step with each other just before the main switches are closed.

The importance of the phase relation becomes obvious if it is recalled that in a 60-cycle, 240-volt circuit the instantaneous voltage swings from 340 volts positive to 340 volts negative and back to 340 volts positive every sixtieth of a second. Consequently, even though the frequency of an incoming generator is the same as that of the line, it is possible to make the unfortunate mistake of closing the main switch or circuit breaker at a moment when, for example, phase *A* of

the incoming machine is at the highest point of its positive voltage swing but phase *A* of the bus is at its greatest negative voltage The resulting effect would be equivalent to a sudden short-circuit of double the normal voltage, and the instantaneous current may under certain conditions rise high enough to damage seriously the generators, transformers, and circuit breakers.

The earliest commercial method of indicating synchronism, and the simplest, is the lamp method. It is still frequently used, and even where a more refined device known as a *synchroscope* (described later) is employed, synchronizing lamps are generally installed as

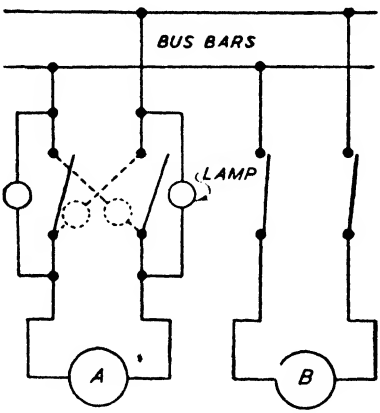


Fig. 6. Lamp Method of Synchronizing Single-Phase Generators

well. The principle employed is illustrated in Fig. 6, representing two single-phase generators, of which *A* is being started in order to synchronize it with *B*, which is already in service and connected to the bus. Since the generator speeds, and therefore their frequencies, differ, their electromotive forces will periodically change from a condition of phase coincidence to one of phase opposition, and likewise the flow of current through the lamps will vary from a minimum to a maximum.

When the electromotive forces of the two machines are exactly equal and in phase, the current through the lamps is zero. As the difference in phase increases, the lamps light up and increase to a maximum brilliancy when corresponding phases are in exact opposition. From this condition the lamps will decrease in brilliancy until

completely dark, indicating that the machines are again in phase. The rate of pulsation of the lamps depends upon the difference in frequency, i.e., upon the relative speeds of the machines.

When the fluctuations of the lamps become very slow, about one in two or three seconds, the frequencies of the two machines are almost the same; the switch may now be closed when the lamps are dark, since at this time the electromotive forces of the two machines are equal. The machines are now operating in parallel and will continue to do so under all ordinary conditions, being held in synchronism by powerful electrical forces.

Synchronizing in the foregoing manner is termed *dark synchronizing.* It is also possible to use *bright synchronizing,* in which case the lamps are connected diagonally across the line switch, as shown by the dotted connection of Fig. 6. Here synchronism is indicated when the lamps are brightest.

Bright synchronizing is not in general use. The lamps glow through a wide range of voltage and it is rather difficult to ascertain the exact moment of synchronism by watching for the maximum brilliancy. Where bright synchronizing is used, carbon filament lamps are to be preferred. These have a negative resistance coefficient, and their hot resistance is about half their cold resistance. Consequently, changes in voltage when the lamps are bright are more noticeable.

For a corresponding reason, when using dark synchronizing (which is the common method), tungsten filament lamps are better. They have a positive resistance coefficient and their cold resistance is only about one-twelfth that when hot. Consequently, they glow down to low voltages and go out completely only when the voltage is close to zero.

The one objection to dark synchronizing is that there is a chance of one of the lamps burning out at the critical moment and thus giving a false indication. However, this possibility can be guarded against by using two independent sets of synchronizing lamps together, or by checking with the indications of the synchroscope.

When the voltage of the system is too high for direct use on the lamps, it is usual to place voltage transformers between the main circuits and the synchronizing lamps, as shown in Fig. 7. This figure also shows the connections for two independent sets of lamps. Note that each set indicates a different pair of phases.

If the connections of either the primary or secondary of either transformer should be reversed from those shown in the diagram,

the indications of the lamps would be reversed; i.e., when the generators are in phase, the lamps would burn at maximum brilliancy, and vice versa.

In order to make certain that the lamps will be dark instead of bright when the machines are in phase, disconnect the main leads of the first generator at the generator and throw in the main switches of both generators with full voltage on the second generator. Since

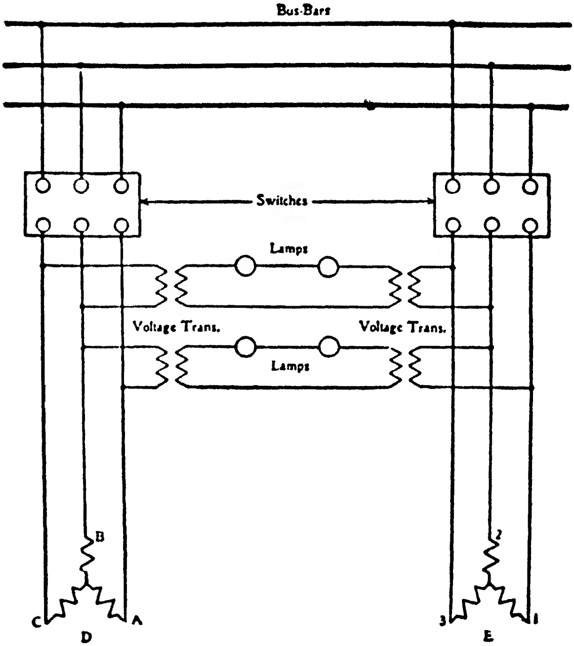


Fig. 7. Connections for Synchronizing Three-Phase Generators
Courtesy of Westinghouse Electric and Manufacturing Co.

both machine circuits are then connected to one machine, the lamp indication will be the same as when the main or paralleling switches are open and both machines are in phase. If the lamps burn brightly, the connections of one of the voltage transformer primaries or one of the secondaries should be reversed.

Phase Sequence. In the case of polyphase machines, it is not only necessary that one phase of one generator be in synchronism with one phase of another generator but also that the sequence of

maximum values of voltage in the several phases be the same. The phase sequence must therefore be checked. The necessary connections for two three-phase generators are shown in Fig. 7.

Connect the generators temporarily to their switches, but with the switches open, so that the phases of *D* will be in parallel with those of *E*. Connect synchronizing apparatus in any two phases. Test out the synchronizing connections with machine *D* running at normal speed and voltage, the leads disconnected from *E* at the generator and the paralleling switches closed. Having changed the synchronizing connections, if necessary, so that both sets of lamps will be dark when indicating synchronism, open the paralleling switches, reconnect the leads of machine *E*, and bring it up to normal speed and voltage. Then observe the two sets of synchronizing lamps. If their pulsations come together, i.e., if both sets are dark and both are bright at the same time, the phase rotation of the two generators is the same, and the connections are correct for paralleling the generators when the lamps are dark. If, however, the pulsations of the lamps alternate, i.e., if one is dark when the other is bright, reverse any two leads of one machine and test out the synchronizing connections again, changing them if necessary so that they are the same when indicating synchronism. The lamps will now be found to pulsate together, and the generators may be thrown in parallel at the proper indication. Phase sequence thereafter need be checked only if some change is made in the wiring.

Synchroscope. A synchroscope, Fig. 8, is an instrument that indicates the difference in phase between two electromotive forces at every instant. By its aid, the operator can see whether the incoming machine is running fast or slow, what the difference in speed is, and the exact instant that synchronism occurs. These conditions cannot be observed with certainty by the use of lamps alone.

The synchroscope has a pointer which shows the phase angle between the incoming and running machines. This angle is always equal to the angle between the pointer and the vertical position marked on the dial of the instrument. When the frequencies of the two machines are equal, the pointer stops at some position on the scale, and when the machines are in phase, the pointer coincides with the marker at the top of the scale.

In order to check the synchroscope connections, proceed in the same manner as previously described for determining whether lamps will be bright or dark for a given synchronizing connection.

The principle upon which a synchroscope works consists of impressing the rotating fields from the running and the incoming machines upon a stator winding. An iron vane armature, free to rotate upon a shaft, then takes up a position dependent upon the resultant value of the two fields, and this position or phase angle is indicated by a pointer attached to the armature shaft. Synchroscopes are not intended for continuous service; as soon as the machines have been

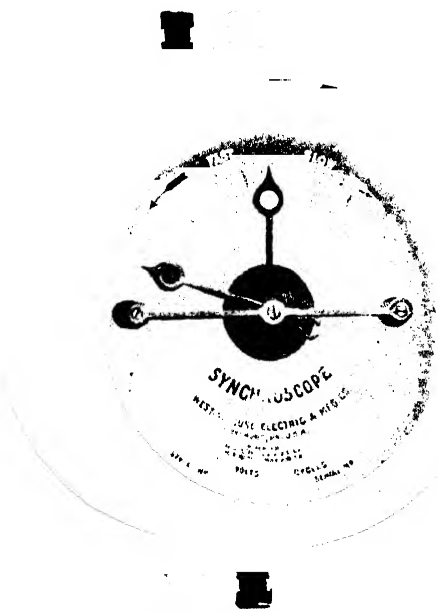


Fig. 8. Westinghouse Synchroscope

paralleled, the synchroscope switch should be opened to prevent overheating of the instrument and its resistor.

Frequency-Matching. A simple method of bringing the incoming machine to the same frequency as the bus, preparatory to throwing in parallel, is to provide the Diesel engine governor with a *speed-matcher*. This consists of two special three-phase squirrel-cage induction motors and a differential gear mechanism. The horizontal shaft of the differential gear mechanism acts through suitable gearing on the speed adjuster of the governor. One motor is connected to the bus and the other to the incoming machine, the first tending to

increase the engine speed and the second to reduce it. The speed-matcher may be put into operation either by a manual switch or by a relay of an automatic synchronizer. Since the motors act in opposition to each other, any difference in speed between the unit and the bus (and consequently the two motors) will cause the horizontal shaft of the differential gear mechanism to set the governor speed adjuster so as to bring the speeds parallel as nearly as possible. When the frequency of the unit and bus are practically alike, both motors will be operating at the same speed; the shaft of the differential mechanism then will cease operation and remain stationary. After the frequencies have been thus matched automatically, it is of course necessary, before closing the main switch to put the incoming machine in parallel with the bus, to see that their voltages are approximately equal and also to wait until the synchronizing lamps or synchroscope shows that the machines are exactly in phase.

Automatic Synchronizing. Of late years, automatic devices to synchronize and parallel an incoming generator with the bus have come into wide use. These devices vary widely in character from simple controls costing about fifty dollars and adapted to small Diesel electric units, to complicated arrangements of relays and electronic tubes costing fifteen hundred dollars or more, designed for plants of the largest size. However, in one respect, all automatic synchronizers are similar; i.e., they must be used with electrically controlled circuit breakers or contactors to connect the machine to the bus.

With an automatic synchronizer, the operator need only start the engine, bring it up to speed, and adjust the voltage, whereupon the synchronizer will do the rest. It eliminates the risk of high current and strain on equipment that is present in improper manual synchronizing and promotes quick paralleling, since the generator is connected to the bus the first time its frequency and phase position become identical with that of the bus.

Simple Voltage-Coil Synchronizers. Typical of the simpler forms of automatic synchronizers is the Westinghouse Type XK, shown in Fig. 9, with cover removed. Referring to the wiring diagram, Fig. 10, it will be noted that the heart of the device is a transformer with three windings, one of which is connected to the generator and another to the bus; the middle winding is connected directly to the coil of the synchronizing relay. When the incoming generator approaches synchronism with the alternating-current bus and then comes in phase with it, the automatic synchronizer relay closes its contacts.

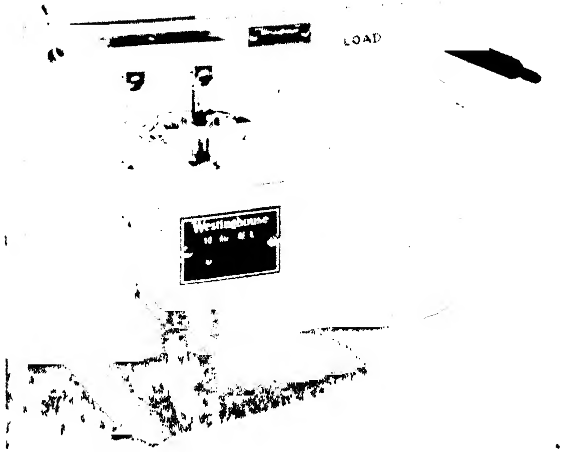


Fig 9 Westinghouse Type XK Automatic Synchronizer with Cover Removed

Courtesy of Westinghouse Electric and Manufacturing Co

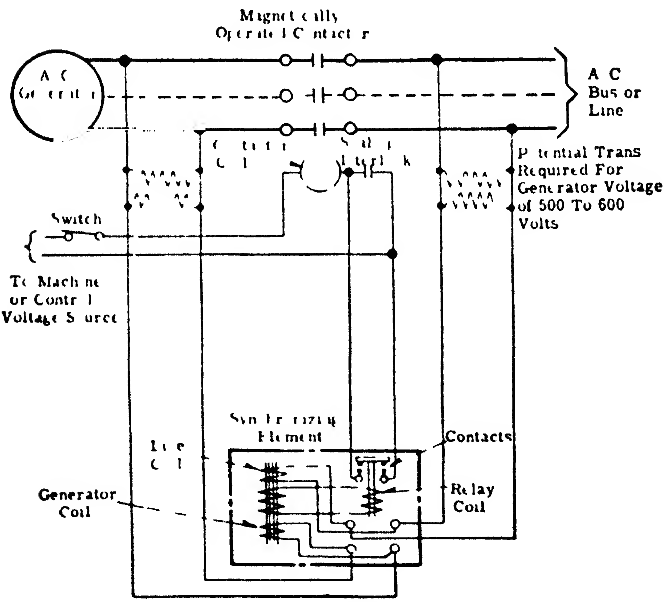


Fig 10 Wiring Diagram of Westinghouse Type XK Automatic Synchronizer

Courtesy of Westinghouse Electric and Manufacturing Co

These contacts are set to close within the zone in which the frequency of the incoming generator is between 97 per cent and 103 per cent or less of the frequency of the alternating-current bus. More precisely, the device operates when the instantaneous voltages on the windings connected to the generator and bus remain equal for a longer period than the time lag due to magnetic hysteresis; this is the case when the frequencies agree within 3 per cent. The closing of the relay contacts, in turn, causes the closing of the generator main contactor or breaker.

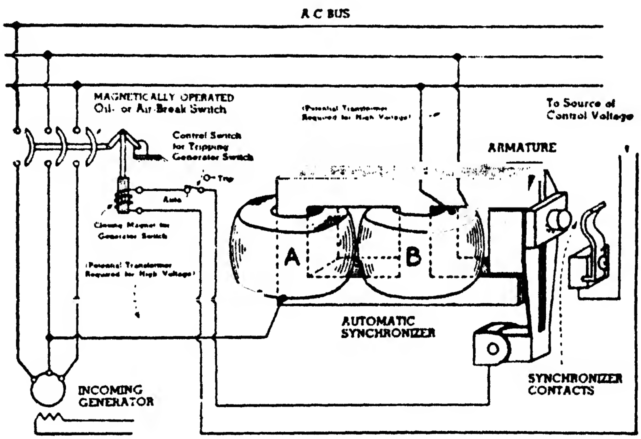


Fig. 11. Diagram Showing Construction and Connections of Automatic Synchronizer

Courtesy of Electric Machinery and Manufacturing Co.

The generator contactor or breaker must be of the fast-closing type (5 cycles or less on a 60-cycle basis) and must be equipped with a sealing interlock, that is, an auxiliary contact which closes when the breaker closes and, being connected in parallel with the synchronizer contacts, insures a complete closing operation of the main breaker. The application of this device is generally limited to generators rated 250 kva, 600 volts or less.

Another simple automatic synchronizer is that built by the Electric Machinery Manufacturing Company and shown diagrammatically in Fig. 11. The laminated core carries two voltage coils, *A* and *B*. Coil *A* is connected to the incoming generator, while coil *B* is connected to the bus. The magnetic force due to the bus current in coil *B* keeps

the synchronizer armature closed and the contacts open, as shown in the figure. When the incoming generator voltage is built up, coil *A* is also energized, but the contacts still remain open. Finally, when the generator frequency comes within 3 per cent of the bus frequency, the armature drops open (closing the synchronizer contacts) at the first coincidence of similar phases.

Burlington Automatic Synchronizer, Type SN. This device employs electronic tubes instead of magnetic coils to indicate phase coincidence. Referring to the elementary circuit diagram, Fig. 12, the fundamental parts are: *impedance* Z for completing a circuit across

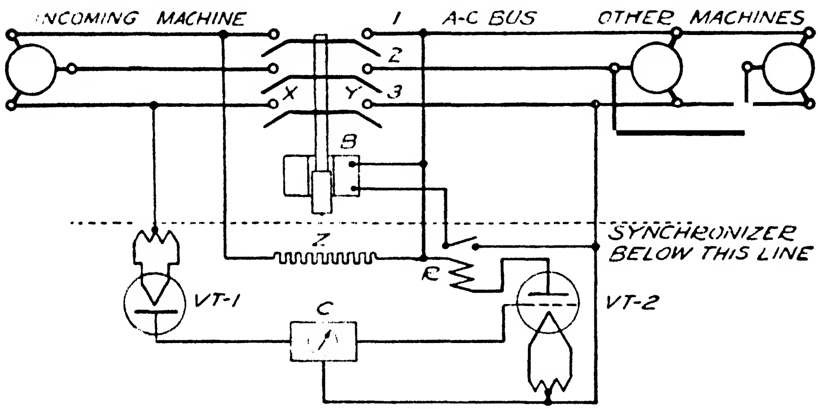


Fig. 12. Elementary Circuit Diagram of Burlington SN-1 Automatic Synchronizer
Courtesy of Burlington Instrument Corp.

a pair of circuit-breaker contacts in one of the phases; *rectifier tube VT-1* for changing the alternating current to unidirectional current; *controller C* for controlling the rate and quantity of current flowing; *grid-controlled discharge tube VT-2* for passing a relatively heavy current; and *relay R* for closing the contacts which operate the circuit breaker *B*.

When the incoming machine is operating and is close to proper frequency and voltage, an oscillating voltage appears across contacts *X* and *Y* in phase 3, the magnitude of which varies from a maximum which is the sum of the voltages of incoming machine and bus to a minimum corresponding to the difference between the voltages of the incoming machine and the bus. The frequency of this oscillating voltage is often termed *slip*.

This oscillating voltage is impressed across the rectifier *VT-1*, which passes unidirectional current and places a negative bias voltage on the grid of *VT-2*. Prior to reaching the grid, this current goes through the control device *C* and is stored there for a definite length of time after the rectifier has stopped passing current. When the oscillating frequency, or slip, is low, and when the voltage difference

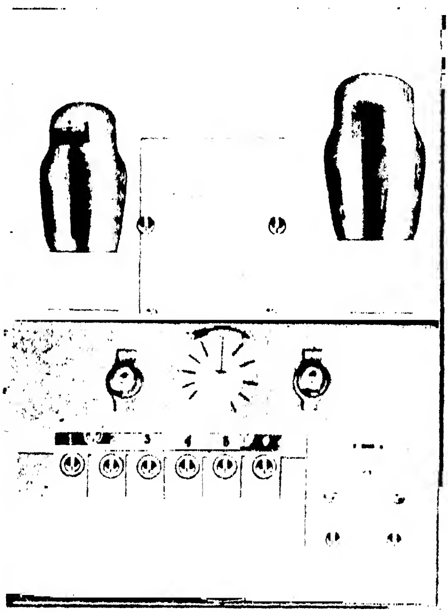


Fig. 13 Burlington SX-1 Synchronizer, with Cover Removed

Courtesy of Burlington Instrument Corp

is low, the grid of *VT-2* loses its negative potential, and a heavy discharge takes place between its plate and filament. The relay *R* then operates to close the circuit breaker.

The time constant of this synchronizer can be adjusted so that the closing takes place at any desired slip frequency from 0 to 10 cycles per second. With large circuit breakers having considerable inertia, the action should be limited to a maximum slip frequency of

less than one cycle per second, whereas with small circuit breakers the permissible slip frequency is 2 or 3 cycles per second.

Since the only moving part is the relay armature which is actuated by heavy current, the operation of this type of synchronizer is little affected by temperature, dust, moisture, or vibration. A view with the cover removed appears in Fig. 13.

Electronic Synchronizers Using Time-Delay Relays. The General Electric and Westinghouse companies both build a more complicated and expensive type of automatic synchronizer which is used in large

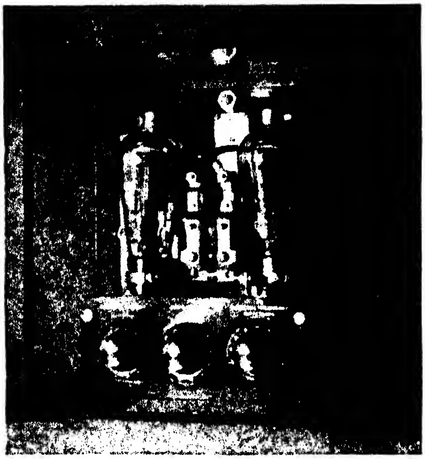


Fig. 14. Westinghouse Type XT Automatic Synchronizer, Showing Tubes
Courtesy of Westinghouse Electric and Manufacturing Co.

plants where accurate, reliable, and positive operation is required. A view of the Westinghouse Type XT Automatic Synchronizer, with cover removed, is shown in Fig. 14.

This type of synchronizer gives the closing impulse to the circuit breaker slightly in advance of synchronism in order to effect closure of the breaker contacts at the instant of zero phase displacement or exact synchronism, regardless of the amount of frequency difference, unless this amount is excessive. If the frequency difference is excessive, the closing indication will not be given. The angle of advance at which the relay functions is proportional to the slip frequency.

Two interlocked relays having different closing characteristics actuate these devices. Relay *A* closes its contacts at a definite phase

angle in advance of synchronism, while relay *B* closes its contacts at a definite time (equal to the circuit-breaker closing time) in advance of synchronism. If relay *A* operates soon enough before relay *B*, the frequency difference is not excessive; and when relay *B* operates, the closing impulse is given to the circuit breaker. On the other hand, if relay *B* operates before *A* (because the frequency difference is excessive), another relay drops out and prevents the closing impulse being given to the circuit breaker. These devices comprise various

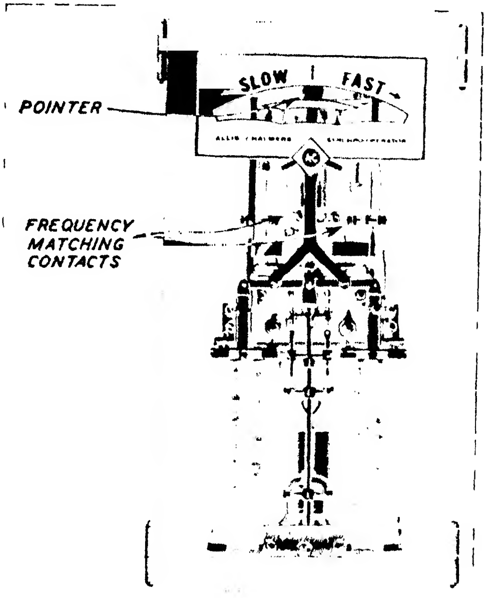


Fig. 15. Allis-Chalmers Synchro-Operator
Courtesy of Allis-Chalmers Manufacturing Co.

other relays, and also rectifiers, electronic amplifiers, etc., to insure accurate and dependable operation.

It should be understood that before these automatic synchronizers go into action it is necessary to bring the incoming unit to correct speed, either manually or by automatic frequency-matching equipment, as described in this chapter.

Allis-Chalmers "Synchro-Operator." This comprehensive device, shown in Fig. 15, combines the two functions of automatic frequency-matching and circuit-breaker closure, and in addition gives a visual

indication of the phase angle which can also be used with manual operation in place of a synchroscope. It uses high-torque solenoids which control silver-to-silver contacts, no electronic tubes being employed. The difference in phase angle is shown by the tip of the pointer, the top-center position being the point of synchronism. A rotation of the pointer in a clockwise direction indicates that the incoming machine is faster than the machines on the bus, and vice versa. This rotational movement operates the frequency-matching contacts which send electrical impulses to the speed-adjusting motor on the engine governor in a direction to equalize the frequencies. At the same time, the phase angle is measured; when this is approaching synchronism, the contacts which operate the circuit breaker are automatically closed at an advanced phase angle proportional to the frequency difference between the machine and the bus so as to allow for the time required for the breaker to close. For frequency differences greater than the safe value, the circuit breaker is not closed. After the breaker is closed, the device is automatically disconnected from the circuit. The operator must then adjust the governor of the incoming unit so that it takes the desired amount of load.

An interesting refinement is that the impulses to the governor speed-adjusting motor are not sent by the frequency-matching contacts until after the point of synchronism has been passed; hence the governor speed setting will never be changing just before or after the circuit breaker closes. The latter might cause an undesired shift in load to or from the incoming machine.

One Synchro-Operator may be used with any number of generators by adding auxiliary relays.

Adjustment of Field Current in Parallel Operation. An alternating-current generator operated in parallel with one or more other generators may have its excitation varied through a fairly wide range while delivering the same kilowatt output at rated voltage. A change in field current under these conditions changes the power factor of the generator. The field current may be set at its rated full load value for all loads or it may be varied, depending upon the need for reactive kilovolt-amperes. If the field current is increased, the generator furnishes reactive kilovolt-amperes to the system and thus relieves the other generators of part of their burden. No change in kilowatt output can be effected by variation of the field current. This can be accomplished only by changing the setting of the engine governor.

The field current should be adjusted so that each generator (if

the units are of equal rating) produces the same amperes as well as the same kilowatts. This would show that they are operating at the same power factor.

Operation with field current lower than the value which gives rated power factor should usually be avoided since this imposes additional load in reactive kilovolt-amperes on the other generators. In addition it reduces the ability of the machine to stay in step with the system and may result in its being pulled out during periods of heavy load.

Automatic Compensation of Reactive Current. When generators operating in parallel are equipped with individual voltage regulators, their power factors can be equalized automatically by connecting a current transformer in each regulator control circuit in such manner that the regulator will reduce excitation when the generator produces more reactive current. Such control of the reactive current is sometimes called *crosscurrent compensation.* It does not require any additional winding on the voltage-sensitive element of the regulator in contrast to the separate compensating winding required on voltage regulators for direct generators in order that their loadings may be equalized.

The compensating action may be followed by referring to Fig. 16. It will be seen that the current transformer is connected across the compensating rheostat, which in turn is in series with the potential transformer that operates the regulator. It is important to note that the current transformer is connected in one generator lead, while the potential transformer is connected to the other two leads. The phase relations are then such that the voltage drop across the compensating rheostat tends to add to the alternating-current potential on the regulator for lagging reactive kva output of the generator and subtract for leading reactive kva output. This influences the regulator to reduce excitation for lagging current (overexcited generator) and increase excitation for leading current (underexcited generator). This action tends to divide the total reactive kva load among any number of machines in proportion to their ratings and enables the regulators properly and automatically to control generators operating in parallel.

Should it be desired to obtain unequal division of reactive current among generators operating in parallel, this can be obtained by adjustment of the compensating rheostats.

This method of crosscurrent compensation tends to introduce a slight droop in the voltage held by the regulators as the reactive-

current loading on the plant is increased. The amount of droop also increases with the amount of resistance used in the compensating rheostats. However, the effect upon plant voltage is usually negligible for load and power-factor conditions encountered in practice.

On some applications there may be reactance connected in between two paralleled alternating-current generators, this reactance being in the form of a power transformer bank, bus reactors, etc. If each gen-

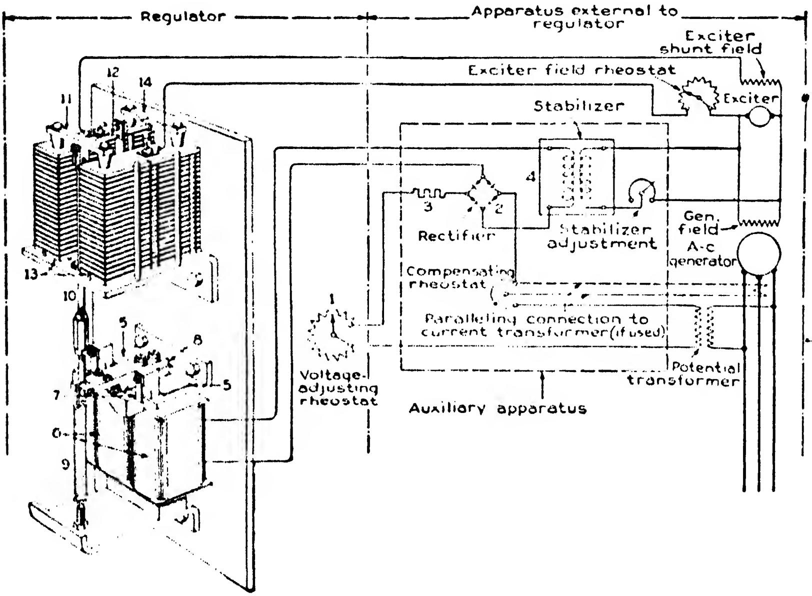


Fig. 16. Wiring Diagram of Voltage Regulator Showing Connections for Crosscurrent Compensation
Courtesy of General Electric Company

erator is excited by an individual nonparalleled exciter under control of an individual regulator, and if the reactance is such as to provide from 4 to 6 per cent reactive drop between the two generators, stable operation can usually be obtained without using crosscurrent compensation between the regulators. This is due to the fact that the reactance produces an effect similar to that obtained where crosscurrent compensation is used.

Excitation Systems, Using Voltage Regulators. Some alternating-current voltage regulators are designed to control only a single gen-

erator, while others, such as those of the relay type can, if desired, be arranged to control the voltage of several generators operating in parallel. The manner in which voltage regulator control is employed in the three excitation systems most often used in Diesel-electric plants is explained in the following paragraphs.

Unit Exciters with Individual Regulators. The unit system consists of an individual exciter and regulator for each alternating-current machine. The exciters are operated nonparallel as shown schematically in Fig. 17. With this method, the voltage of each alternating-current

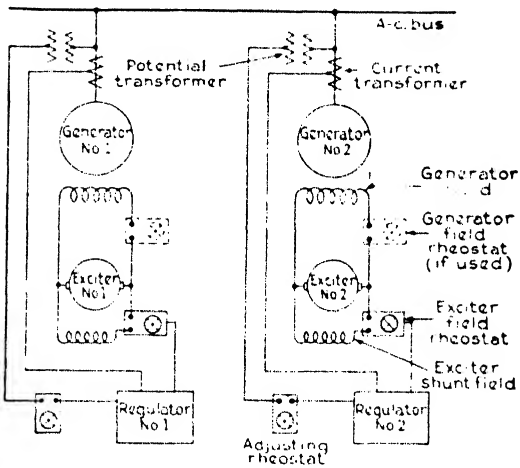


Fig. 17. Diagram Showing Individual Regulators for Two Generators Operating in Parallel
Courtesy of General Electric Co.

machine is automatically and independently controlled by its own regulator, and the division of reactive kilovolt-amperes among machines is automatically controlled by alternating-current compensation of the regulator from a current transformer in the manner previously described. With this system, there is no problem of load division among exciters, as each operates independently.

Unit Exciters with Common Regulator. Each alternating-current machine field is excited from an individual exciter (operated nonparallel), and all are controlled from a single regulator. A diagram of this scheme is given in Fig. 18.

If the regulator is of the vibrating type, each exciter is controlled by a separate relay which shunts that exciter's field rheostat, and

all the relays are controlled simultaneously from the single regulator control element.

If the regulator is of the rheostat type, each exciter is controlled by a separate rheostat in the exciter field circuit, and all the rheostats are operated simultaneously from the single regulator control element.

With this method, the regulator provides completely automatic control of alternating-current voltage, but division of reactive kilovolt-amperes among alternating-current machines and load division among exciters requires manual control. Manual control consists of adjust-

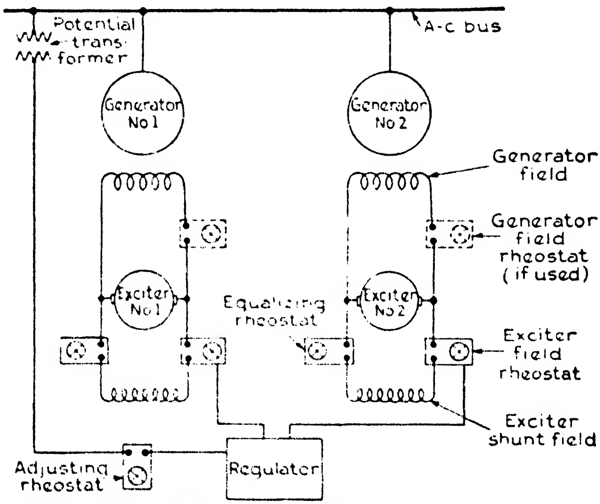


Fig. 18. Diagram of a Single Regulator Controlling Two A.C. Generators Operating in Parallel
Courtesy of General Electric Co.

ment of the exciter-equalizing rheostats, the main generator-field rheostats, or both rheostats combined.

Common Exciter Bus and a Common Regulator. The alternating-current machine fields are excited in parallel from a variable-voltage exciter bus supplied by one or more exciters. All of the alternating-current machines are controlled from one regulator, with the appropriate number of relays or rheostats applied to each exciter-field circuit. This scheme is shown diagrammatically in Fig. 19.

The alternating-current bus voltage is under full-automatic control of the regulator. The division of reactive kilovolt-amperes among alternating-current machines in parallel is controlled manually by

adjustment of the main generator field rheostats. Division of load among exciters operating in parallel is controlled manually by adjustment of the exciter-field-equalizing rheostats, as shown in Fig. 19.

The unit system of excitation with individual regulators has many advantages, such as completely automatic control of reactive kilovolt-amperes as well as voltage, lower rheostat losses, increased generator efficiency, simplified synchronizing and elimination of exciter paralleling difficulties. On the other hand, the cost of individual regulators

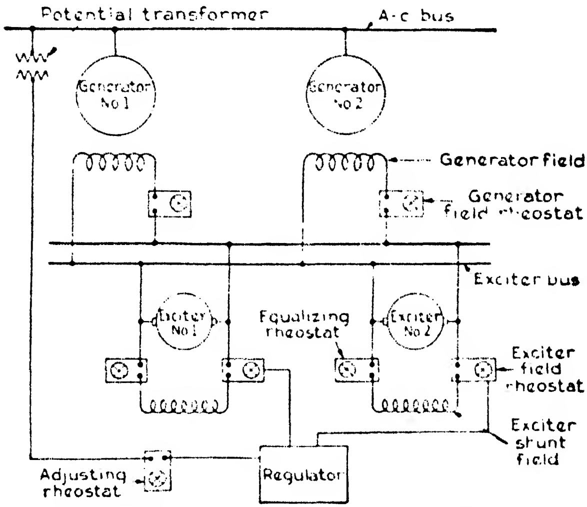


Fig. 19. Diagram of a Single Regulator Controlling Two Paralleled Exciters
Courtesy of General Electric Co.

for each machine, especially in small-sized plants, may be greater than that of a single regulator capable of controlling all the machines.

Coordination of Engine and Generator Characteristics. In order for engine-driven alternating-current generators to operate in parallel successfully, certain characteristics of the units themselves should be coordinated with each other. If this is not done there may be difficulties in load-sharing, hunting in speed, excessive electrical cross-currents, etc. Such troubles will be avoided if the following requirements are met:

1. The speed regulation (speed droop) of the Diesel engines should be alike. That is, the per cent drop in speed for a given per cent increase in load, should be the same on all units. The drop in

speed from no load to full load may be only 2 per cent or less, but if it is the same on all units which are in parallel, the total load will divide between them in proportion to their ratings.

2. The governors of the Diesel engines should be free from hunting and should bring the machines to a steady speed without delay. Any oscillation of the governors will result in a transfer of load back and forth between machines and a fluctuation of the voltages.

3. The generators should be equipped with damper or amortisseur windings. These increase the synchronizing forces, reduce the fluctuations in rotor speed due to the engine firing impulses, and thus limit the crosscurrents.

4. Voltage regulators should be provided with adequate crosscurrent compensation.

5. The total flywheel effect of each unit should be such that:

a) During parallel operation the maximum periodic displacement of the rotor in either direction from the position of uniform rotation should not exceed 3½ electrical degrees.

b) The natural frequency of oscillation of the unit should differ at least 20 per cent from the frequency of any forced impulse of any of the engines operating in parallel.

Small high-speed Diesel engines generally have ample flywheel effect to meet these conditions, but care is needed in the case of slow-speed engines, particularly those with few cylinders.

The critical frequencies to be avoided are as follows:

1. For a four-cycle engine: particularly one-half the revolutions of the engine crank but also the revolutions of the crank.

2. For a two-cycle engine: particularly the revolutions of the engine crank, but also two times the revolutions of the crank.

A table of critical frequencies to be avoided follows.

Critical Frequencies To Be Avoided

Number of Cylinders	Four-Cycle Engines			Two-Cycle Engines		
	1st Order Frequency	2d Order Frequency	3d Order Frequency	1st Order Frequency	2d Order Frequency	3d Order Frequency
2	0.5 *n*	*n*	......	*n*	2 *n*	......
3	0.5 *n*	......	1.5 *n*	*n*	......	3 *n*
4	0.5 *n*	*n*	2 *n*	*n*	2 *n*	4 *n*
5	0.5 *n*	......	2.5 *n*	*n*	......	5 *n*
6	0.5 *n*	*n*	3 *n*	*n*	2 *n*	6 *n*
8	0.5 *n*	*n*	4 *n*	*n*	2 *n*	8 *n*

n = Engine r.p.m.

For any given unit the natural frequency at which the rotor tends to oscillate can be changed by changing the flywheel effect, as shown by the following relation:

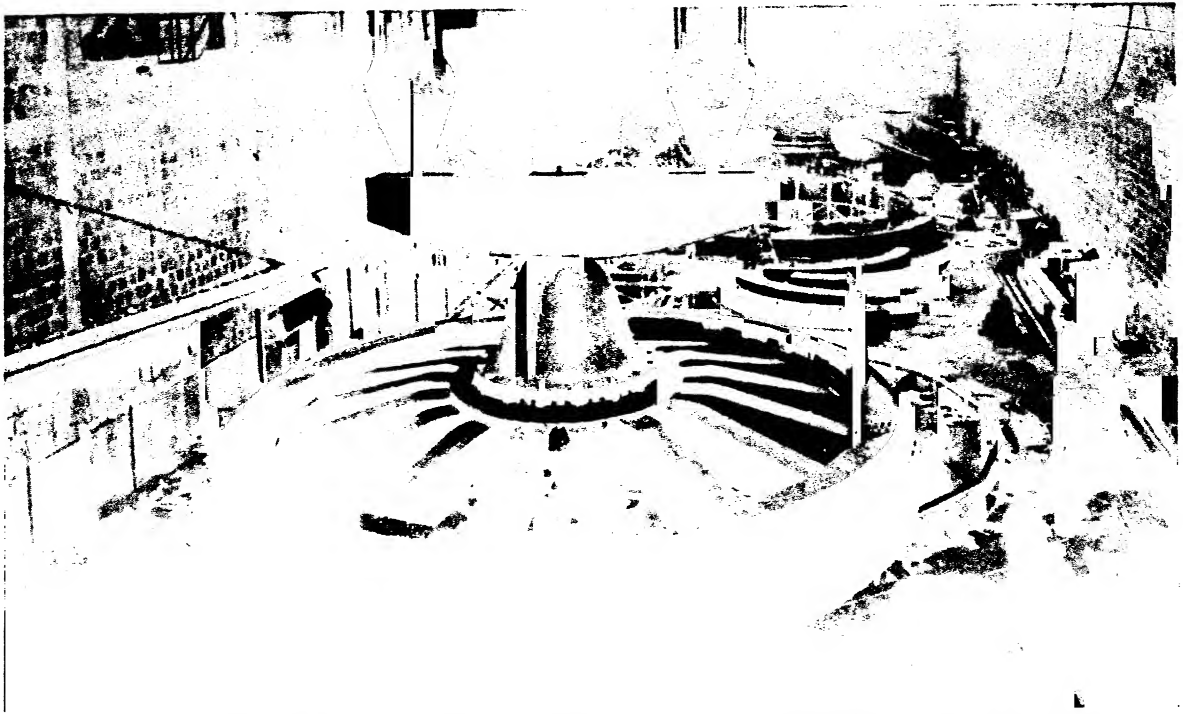
$$F = \frac{35{,}200}{\text{r.p.m.}} \sqrt{\frac{P_r \times f}{WR^2}}$$

where F=natural frequency in periods or beats per minute
r.p.m.=revolutions per minute.
P_r=kw output at synchronous speed corresponding to the torque exerted on the rotor per radian displacement. This is a constant furnished by the generator manufacturer.
f=frequency of generator in cycles per second.
WR^2=flywheel effect in lb-ft.^{2}

(The term *radian*, used to define P_r, means the angle subtended by an arc of a circle equal in length to the radius of the circle. Angles are frequently expressed in radians in order to simplify mathematical formulas. The value of a radian is 57.29578 degrees.)

The value of P_r is approximately 3.2 times the kw rating of the generator, but varies somewhat with the speed and general design.

Example. For a 60-cycle, 150-r.p.m., direct-coupled generator having a value of P_r=1,420, and driven by a four-cycle engine, the natural frequency must not lie between 60 and 90 periods per minute, or between 120 and 180 periods per minute. That is, the total WR^2 (flywheel and generator) must not lie between 1,305,000 and 580,000 lb-ft.^{2}, or between 326,000 and 145,000 lb-ft.^{2}



ROTOR OF A 30,000-KVA, 13,800-VOLT, 75-RPM WATER-WHEEL ALTERNATOR CONTAINING 96 POLES AND WEIGHING ABOUT 225 TONS, STATORS ARE ASSEMBLED IN PITS SHOWN IN BACKGROUND

Courtesy of Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin

MANAGEMENT OF HYDROELECTRIC MACHINERY

Introduction. This treatise is intended to convey to the operator of a hydroelectric plant some idea of what his duties are, how to take care of his equipment and keep it in good running order and repair, and also how to determine whether it is run economically or not.

The service which a hydroelectric generating station can give depends to a great extent not only on the type of equipment but on the manner in which it is maintained. Attention should be called to the minutest detail of construction; it is poor economy to install up-to-date alternators and turbines and try to protect them with inferior auxiliary equipment. One small defective relay may put an alternator out of commission.

The present trend of engineering is toward full automatic operation and control, and the more up-to-date hydroelectric stations are being controlled by means of the audible type of supervisory control. This control, however, applies to the small generating station only; although it will be but a short time before any size station can be automatically and remotely controlled. By means of this type of supervisory control, practically any number of stations may be entirely controlled over a single pair of wires, the same wires being also used for telephone service between the stations. With this system of control, the operators at the various stations are under the direct supervision of a central load dispatcher. By means of this control, code points may be arranged to signal the dispatcher the amount of water available in the forebay, the waterwheel gate opening, the position of the oil circuit breakers or the position of any other apparatus. The available working head of water is divided into ten equal parts and the signals run from 1 to 10. The same applies to the gate opening. The position of the circuit breakers is also indicated either open or closed by means of signals. The water turbines and alternators can be started and stopped, load increased or decreased and the station paralleled with others, the dispatcher

knowing at all times what is being done. So sensitive is this control that stations of one machine only may be controlled automatically, no operator being required.

The duties of an operator do not stop at merely starting up and shutting down the various machines, but include a thorough and periodical inspection of all main and auxiliary apparatus. The following list comprises practically all the duties of an operator:

(1) Inspection of turbines and turbine auxiliaries, such as gates, governors, etc.
(2) Oiling of the above
(3) Inspection of alternators and exciters
(4) Oiling of the above
(5) Starting up the turbines, alternators, and exciters
(6) Shutting down the above
(7) Inspection of heat detecting apparatus on alternators
(8) Hourly or half-hourly readings of all station meters
(9) Daily inspection of all oil circuit breakers and open type disconnects for excess heating and discoloration
(10) Inspection of transformer temperature and cooling medium, whether oil, water, or air
(11) Inspection of all voltage regulators
(12) Inspection and charging of lightning arresters
(13) Inspection of current limiting reactors
(14) Inspection and recharging of storage batteries for solenoid control on oil circuit breakers
(15) Care and inspection of all instruments, such as synchroscopes, frequency indicators, wattmeters, voltmeters, and ammeters
(16) Frequent testing and checking of all the above instruments against known standards
(17) Keeping plant and all equipment clean

CARE AND MAINTENANCE OF ALTERNATORS

The following instructions are for the proper care and maintenance of alternators and auxiliary equipment.

(1) The bearings should receive considerable attention. Most water-wheel alternators are of the vertical type and are therefore equipped with thrust bearings. The bearings are all equipped with sight-feed oil cups, or else oiled under pressure by means of oil pumps, or, as in some cases, they are lubricated with grease under pressure. On some installations the bearings are equipped with telltales which indicate, by means of either audible or visual signals, the condition of the bearing at all times. When so equipped, the signal circuit should be tested at least once every shift.

(2) The temperature of each alternator should be noted every hour when under load. The standard practice in most generating stations is to equip alternators with signalling apparatus as a protection against overheating and damage

to insulation. At certain spots in the stator (usually from 4 to 6) resistance thermometers or thermocouples are situated, these being connected to recorders which indicate the temperature of the incoming and outgoing air on a continuous chart. In addition to the recorder, alarm bells or lights are connected in the circuit to signal when any of the hot spots reach a dangerous temperature. The recorder and signal circuits should be tested periodically.

(3) The exciters should be kept clean, the commutators should be kept undercut, and the brushes should be kept loose in the holders and renewed when the brush pressure against the commutator falls below one and one-half pounds per square inch.

(4) The voltage regulators should be kept clean and the contacts bright. The resistances should be regulated as outlined under the care of voltage regulators.

(5) All bus work and cables, potheads, etc. should be kept clean and should be inspected from time to time to ascertain if there is any excess heating in any part of the system.

(6) The air gap between the alternator rotor and stator and between the exciter field and armature should be checked periodically to ascertain any wear of the bearings and that the revolving parts are properly centered.

Troubles of alternators

Some of the troubles encountered with alternators are the same as those of synchronous motors, since there is very little difference between the two machines, so that only those peculiar to alternators alone will be given here.

Symptom 1—Alternator fails to build up

Trouble
(a) Prime mover not up to proper speed
(b) Open circuit in alternator stator windings
(On most alternators the stator windings are paralleled two or more times and therefore this trouble does not show up unless the windings are series star connected. If delta connected, the alternator will build up on open delta.)
(c) Open circuit in alternator field rheostat
(d) Open circuit in rotor or field windings
(e) Exciter not functioning

Cause
(a) (1) Gates not opened enough or low water
(2) Governor cutting off too soon
(b) Short circuit which may have caused one or more coils to burn out
(c) Overheating of resistances or damage by vibration or other cause
(d) Connections between field coils broken or burned, or a burn out in one or more field coils
(e) (1) Open circuit in exciter armature
(2) Open circuit in exciter field
(3) Open circuit in exciter field rheostat
(4) Brushes not in contact with exciter commutator
(5) Brushes not in proper position on commutator

Remedy (a) (1) Examine gates and water level. Adjust gates. Let more water in forebay

(2) Adjust governor so as to allow prime mover to come up to maintain normal full speed

(b) Remove coil which is open and replace with a new one

(c) Test with a Megger, magneto, or lamp circuit to locate open section, jump the break or insert a new resistance grid

(d) Test out as outlined above and if only the connections are broken, reconnect. If field coil is gone, either replace with a new one or rewind the old.

(e) (1) Test and repair as outlined in the text and illustrated by Fig. 4 for parallel windings, and by Fig. 5 for series windings

(2) Test with a Megger, magneto, or lamp circuit to locate open section, jump the break or insert a new resistance grid

(3) Test and jump the break in the resistance or renew the defective section

(4) Loosen brushes in holders. Renew brushes if short

(5) Move brushes forward until the exciter builds up

Symptom 2—Alternator voltage fluctuates and alternator issues a sound which changes in volume

Trouble Alternator hunting

Cause Unstable speed of waterwheel due to some defect in the governor

Remedy If a Westinghouse flyball governor is used, there should be very little trouble, as this is one of the best antihunting devices to be found. If, however, trouble is encountered and it is found to be in the governor, (1) clean out the dashpot and change the oil for a heavier grade if the dashpot acts too freely or for a lighter grade if the dashpot has a tendency to be sluggish; (2) place a small quantity of fine oil on the various lever bearings; (3) look over the pilot valve to see that it opens and closes on the action of the flyball; (4) see that the centering springs both have the same tension

Practically the same procedure may be followed with other types of waterwheel governors.

Symptom 3—One or more hot spot indicators register that the temperature of the alternator has reached the danger point

Trouble Stator windings overheated

Cause (a) Overload

(b) Short circuit in stator windings

(c) Rotor not in exact magnetic center with respect to the stator

(d) Low power factor of load

Remedy (a) Reduce the load if possible. Start another machine if available

(b) A short circuit in any winding or group will cause the insulation to be completely burned off the windings if left for any length of time. If noticed as soon as the heating starts, the insulation can be saved. If the alternator is badly needed, temporary repairs can be made by cutting out the defective coil or coils and connecting those adjacent to them in circuit. Care must be taken that the

coils so connected are in their proper groups and that the polarity of the reconnected groups are the same as before.

(c) If the bearings become worn so as to allow the rotor to touch the stator core, the windings under the shortened air gap will heat up to a greater extent than those adjacent to them, with the result that the wedges over the windings will become charred and the insulation scorched. If discovered in time, no real harm will be done. Changing the bearings is the only practical method of remedying a fault of this kind.

(d) If the load on the alternator is inductive, i.e., consists of induction motors, its rating is determined by the power factor of those motors. For instance, if a 1000 kilovolt-ampere alternator is supplying an inductive load, the power factor of which is 80 per cent, the alternator is fully loaded when delivering 800 kilowatts. The only remedy in a case of this kind, if the inductive load at its rated power factor exceeds the rating of the alternator, is to reduce the load or start another alternator if available.

Symptom 4——Alternator slows down when carrying load

Trouble (a) Prime mover slows down
(b) Overload

Cause (a) Low water. Governor not functioning properly
(b) If more than one alternator is supplying the bus, the overloaded alternator is supplying more than its share to the load.

Remedy (a) Increase the volume of water to the turbine. Adjust the governor so that it operates more quickly on change of load.
(b) Adjust the alternator field rheostat so that the offending alternator is dividing the load equally with the others.

Symptom 5——Voltage of all alternators fluctuates

Trouble (a) Loss of excitation on one or more alternators
(b) Prime movers alternately racing and slowing down

Cause (a) (1) Open circuit in exciter circuit
(2) Open circuit in alternator field
(b) (1) Not enough water in forebay
(2) One or more governors not functioning

Remedy (a) (1) Test out exciter external circuit, including the brushes, armature windings and field windings, as outlined under exciter troubles, under symptom 1, troubles (d) and (f), also text following that table.
(2) Test out the brushes and collector rings, also the field windings of alternator, with a Megger or low voltage circuit
(b) (1) Open dam gates in storage reservoir
(2) Oil and adjust governors to the proper alternator speed

Symptom 6——Voltage too low

Trouble (a) Speed of prime mover too low
(b) Excitation too low
(c) Load too great

Cause (a) Lack of water. Governors not functioning properly
(b) (1) Too much resistance in alternator field
(2) Exciter voltage too low
(c) Overloaded lines

Remedy (a) Speed up prime mover by increasing the amount of water to th turbines. Adjust governors for higher speed operation.
(b) (1) Cut some of the resistance out of the alternator field circuit
(2) Increase the voltage of the exciter or exciters by cutting out some of the exciter field resistance
(c) Reduce the line load or add another alternator to the system

Symptom 7—Voltage too high

Trouble (a) Speed of prime mover too great
(b) Excitation too high

Cause (a) Governors out of adjustment
(b) Not enough resistance in series with alternator fields

Remedy (a) Adjust governors for lower speed
(b) Adjust field rheostats and regulators so that there will be more resistance in series with the alternator fields

Starting of alternators

The procedure to be followed in starting up an alternator is summed up in the following instructions.

(1) Examine the bearings to see if there is plenty of oil, and that the oil rings are free to turn.

(2) Make sure the alternator is disconnected from the main bus.

(3) Start and bring the exciter up to speed, after which the voltage should be adjusted to normal. (The above applies only to machines excited from exciters driven by separate prime movers and not to those which are direct connected to the exciter.) For direct connected types, the exciters are brought up to speed with the alternators and the exciter voltage adjusted before excitation is applied to the alternator.

(4) Start the alternator slowly by opening the gate to the turbine. Gradually increase the speed until the alternator attains full speed, at which time the turbine is put on the governor. If the machine is of the vertical type, see that the oil pressure gauges are indicating that oil is circulating the bearings.

(5) Adjust the alternator field rheostat so that the proper amount of resistance is in series with the field as outlined in the operation and maintenance of voltage regulators.

(6) Close the field switch, if manually operated, which applies excitation to the revolving field of the alternator. If excitation is applied automatically, it will be applied through the operation of relays and hesitating coils at the proper moment. After the field switch is closed, if the excitation is manually applied, the alternator field rheostat should be adjusted for normal operating voltage. If the alternator field is supplied with automatic voltage regulators, the proper amount of excitation will be given if the hand field rheostat is adjusted as outlined under the care of voltage regulators. If field excitation is applied automatically and voltage regulators are supplied, the alternator voltage will be

adjusted automatically and will require no attention outside of a casual inspection to assure that the automatic apparatus is functioning properly.

(7) The main oil circuit breaker connecting the alternator to the bus may then be closed if only one alternator is operating. If an alternator is to be started and paralleled with one already running the following procedure should be noted.

Cutting in an alternator to a bus to which alternators already running are connected

(1) Follow the procedure as just stated up to and including instruction No. 6; only instead of the alternator voltage being normal, it must be exactly the same value as the voltage of the main bus.

(2) Synchronize the incoming alternator with those running or with the main bus so that they are exactly in phase. (See voltage regulators.)

(3) Close the circuit breaker on the incoming alternator, connecting it to the main bus and load.

(4) Adjust the voltage of the incoming alternator so that no cross or circulating currents will flow between the various machines.

(5) Adjust the governors of all prime movers and the voltage regulators of all alternators until the load is properly distributed between all the alternators in proportion to their size and capacity.

Cutting out an alternator which is paralleled with others

(1) Reduce the load on the alternator to be cut out by cutting down the speed of its prime mover so that it will carry the alternator at no load only.

(2) Adjust the alternator field rheostat until the excitation and the current in the stator winding are at a minimum.

(3) Open the alternator circuit breaker, disconnecting the alternator from the main bus.

(4) Open the alternator field switch and bring the prime mover to a stop.

Note: The alternator field switch must never be opened before the circuit breaker connecting the alternator to the bus is opened as this would cause a heavy current to flow between the stators of all the alternators.

(5) Adjust the voltage on the remaining or running units if they are not provided with automatic regulators, as they will now be carrying all of the load.

Field adjustments of alternators in parallel

When the field rheostats of two or more alternators connected in parallel are not properly adjusted to give the amount of excitation required by the characteristics of each machine to maintain the same voltage, cross or circulating currents will flow between the armatures or stators of these alternators. The intensity of this circulating current will vary as the difference in the excitation of the two machines, and it will be zero when the proper amount of excitation is given up to full load current if one machine drops its excitation.

This circulating current raises the temperature of the windings and decreases the output of the alternators. One method of detecting these currents is by the readings of the ammeters. If the ammeter readings are higher than normal and a check of the totalizing wattmeter shows that the load is no higher than normal, it is a sure indication that circulating currents are flowing between the various machines. When the ammeters show the minimum readings for a given load, the cross or circulating currents are zero.

Prevention of hunting

Hunting describes the oscillations of the revolving masses of alternators when they are accelerated above and retarded below normal speed. When this condition becomes aggravated, the regulation of the alternators becomes unstable and may cause them to fall out of step with each other. For proper regulation it is necessary that all alternators be in step or in synchronism, i.e., they must all reach their maximum and zero values at the same instant. Failure to accomplish this condition may be due to low water, improper adjustment of governors, improper adjustment of regulators, or from inertia of the rotating masses.

To prevent hunting in water wheel alternators, the following method may be employed:

(1) Adjust the water turbine governor so that it acts instantly on load and water fluctuations. If the governor is of the dashpot type, changing the oil or shortening the travel of the piston will remedy the fault.

(2) Adjust the voltage regulators of the various machines. If all alternators have the same characteristics, the field rheostats should all be in the resistance out position, or nearly so. If the characteristics of the various machines differ and one regulator is used for the control of them all, the resistance should be cut in the fields of those alternators taking the wattless current or which operate at low power factor, and those operating at high power factor should have their field resistance all cut out, and those operating at intermediate power factors should have their rheostats adjusted slightly in the resistance in position.

What to do when one or more alternators drop out due to an electrical storm

In the event of an electrical storm, one or more or all of the alternators of a station may drop out. To prevent this occurrence as far as possible, current limiting reactances are usually connected

in series with each alternator; but even these may not prevent some or all of the alternators from dropping off the bus or line. In the case of automatically operated stations, the breakers will close three times and if the trouble has cleared itself on the third closing, normal operation is resumed. If, however, the breakers open for the third time, they have to be manually set by means of a pilot circuit or other means after the trouble is cleared.

For resuming normal operation after a shut down due to the above cause where manual starting is necessary, the procedure described under starting and paralleling alternators must be resorted to.

What to do when an alternator looses its excitation

If two or more alternators are paralleled and one of them drops its excitation, it will draw a heavy current in its stator windings from the other alternators, and at the same time a heavy current will be induced in its rotor or field winding. This current will be alternating and since the rotor and stator magnetic fields are not locked as normally when under excitation, this current will impose a heavy load on the alternator and tend to slow down its prime mover. The remaining alternators in order to carry their share of the load and that of the non-excited alternator will impose a greater load on their respective prime movers, with the result that if the voltage regulators are connected with the turbine governors, the regulators will respond, open the valves, and speed up the remaining alternators. If this state of affairs persists for any length of time, not only the offending alternator but all of the alternators will heat up.

As soon as a condition of this kind is apparent, the offending alternator should be shut down and the load adjusted so that the remaining alternators are not overloaded. The exciter circuit and alternator field circuit are then examined and tested for fault; when repaired, the offending alternator is again put into operation.

CARE AND MAINTENANCE OF EXCITERS

Since an exciter is a direct-current generator, it requires a considerable amount of attention if it is to function properly and give a maximum of service. Among the various points to consider in the proper maintenance of an exciter are:

(1) The bearings must not become worn; otherwise the armature will strike the pole pieces, tear the armature bands off, and heat up the armature and field coils.

(2) The commutator must not be allowed to become grooved; since when grooved, the brushes will take the same form as the commutator and cut the grooves deeper. Grooving may be eliminated by increasing the end play of the armature and by staggering the brushes. In staggering the brushes, the brushes of unlike polarity should line up as shown in Fig. 1. Since the wear is at the positive brush, a negative brush should be parallel with it. The diagram shows the position of 4 sets of brushes, 2 sets of negative and 2 sets of positive. This arrangement not only prevents grooving but assures an even wear over the whole surface of the commutator, and eliminates the formation of ridges.

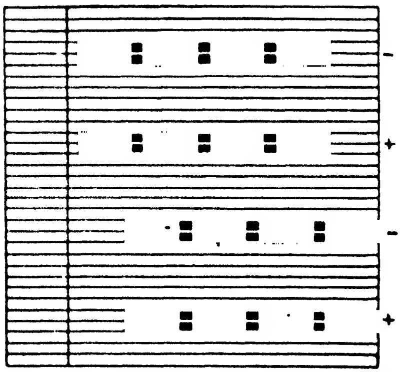


Fig. 1. Proper Method of Staggering Brushes on a Commutator

(3) If ridges form on the commutator, they should be removed by the use of a commutator stone or by a lathe cutting tool. A commutator stone will do the better job, and the armature does not have to be removed nor the exciter taken out of service. After smoothing the commutator by means of a stone, the brushes should be loosened in their holders, since they nearly always become wedged by the fine particles of copper, mica, and stone dust. Care must be exercised in using a commutator stone that too much pressure is not put on the stone. The stone should be held firmly either on a rest or on a set of brush holders toward which the commutator is turning and the stone allowed to swipe the bars as they pass under the stone. If care is not used in this respect, the commutator might become oval shaped, especially if slightly oval in the first place or if there are any burned or flat spots.

(4) The mica should be undercut between all of the commutator bars. Undercutting a commutator eliminates high bars and singing and flashing at the brushes. Undercutting may be done with a three-cornered file, a piece of hacksaw blade or by means of the various power-driven undercutting tools. The commutator should never be cut deeper than from $\frac{1}{32}$ inch to $\frac{1}{8}$ inch at any one time.

(5) The brushes should never be allowed to become so short that they barely touch the commutator, and they should have a pressure against the commutator of one and one-half pounds per square inch. Brushes should be of a grade that will not cut the commutator. It is much greater economy to replace brushes than it is to replace a commutator. The brushes, however, should not be too soft, since a soft brush will wear too fast and blacken the commutator and increase the resistance between the brush and the commutator.

(6) The commutator should be kept a bright copper color rather than a deep chocolate color on account of the resistance mentioned above.

(7) If a commutator stone is not available, the use of fine sandpaper is recommended. (**Caution:** Never use emery paper or cloth.)

Troubles of exciters

The troubles that are likely to occur in a direct-current generator or exciter and their causes and remedies are found in Table I.

Repairing short circuits in exciter armature windings

A short circuit in an armature coil will cause the coil to heat more than those adjacent to it. When located, a short-circuited coil may be cut out and the exciter operated without it, the only effect

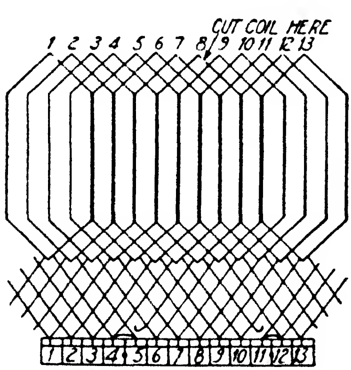


Fig. 2. Wrong Method of Connecting a Jumper in a Single-Series Winding

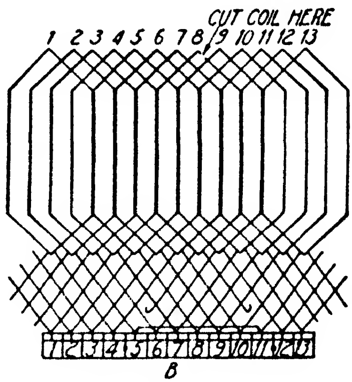


Fig. 3. Correct Method of Connecting a Jumper in a Single-Series Winding

being that the load rating is slightly decreased. Care must be used in cutting out a coil, since the method varies with the type of winding.

With a single parallel winding, a defective coil is cut out as shown in Fig. 2. First, the coil is cut at the back of the armature, as shown in the diagram. Next, the commutator bars to which the defective coil is connected is located by a lamp circuit or a magneto. When

TABLE I

Troubles of Exciters

Symptom	Trouble	Cause	Remedy
1. Exciter fails to build up	(a) Residual magnetism destroyed	(a) Residual magnetism lost through non-use	(a) Charge fields with another d.c. generator, or with a battery of dry cells; making sure the fields are connected for proper polarity.
	(b) Residual magnetism reversed	(b) (1) Reversed current through field coils	(b) (1) Connect fields for proper polarity, run the exciter above rated speed if possible, short circuit the armature at the brushes, or tap the pole pieces with a hammer. Usually one of these methods will cause the exciter to build up. If, however, these methods fail, then charge fields with another d. c. generator or with a battery of dry cells. The polarity should be tested with a compass both before and after.
		(2) Earth's magnetism	(2) Connect fields for proper polarity, run the exciter above rated speed if possible, short circuit the armature at the brushes, or tap the pole pieces with a hammer.
		(3) Proximity of another d.c. machine	(3) Connect fields for proper polarity, run the exciter above rated speed if possible, short circuit the armature at the brushes, or tap the pole pieces with a hammer. Connect exciters so that their magnetism is opposed and they do not affect one another.
		(4) Brushes shifted so that commutation is in the opposite direction	(4) Shift brushes in the direction of rotation, or back and forth until exciter builds up.
	(c) Short circuit in armature	(c) Carbon dust between adjacent commutator bars or insulation of coils broken down	(c) Clean the commutator. The presence of this trouble will be denoted by flashing of the brushes, or by heating of one or more coils. Rewind if insulation is gone.
	(d) Open circuit in armature	(d) Rough usage or original short circuit which may have burned a coil or connection	(d) Test out adjacent commutator bars and locate the trouble. Bridge the gap as a temporary expedient, insert a new coil, or rewind the whole armature.

TABLE I—Continued

Troubles of Exciters

Symptom	Trouble	Cause	Remedy
	(e) Short circuit in fields	(e) Dampness or defective insulation	(e) Bake if former, rewind if latter. (NOTE: a short-circuited field coil will be cooler than its neighbors, since its share or part of its share is imposed on the others.)
	(f) Open circuit in field or field connections	(f) Rough usage or original short circuit which may have burned a coil o connection	(f) Examine field connections and test with a magneto or voltmeter, and if coil is open, rewind or replace it.
	(g) Short circuit in external circuit	(g) Collector rings of alternator short circuited or short circuit in voltage regulator circuit	(g) Search for trouble by sectionalizing the exciter external circuit and removing the cause. In a case of this kind the exciter will try to build up and the brushes will flash at the commutator. If properly protected by fuses or a circuit breaker, the machine will clear itself from the line. A series-wound exciter will not build up.
	(h) Fields opposed to each other	(h) (1) Field coils of either a shunt or series exciter connected for the same polarity	(h) (1) Change connections between field coils and test with a compass for opposite polarity of adjacent coils. When adjacent coils show opposite polarity, the exciter should build up if this is the trouble.
		(2) Shunt and series fields of a compound wound exciter connected for proper polarity individually, but connections of exciter so made that they oppose or buck each other	(2) Change polarity of either field, but don't change the connections of both, as the same trouble will occur again.
	(i) Exciter running backward	(i) Prime mover travelling in wrong direction	(i) Reverse direction of rotation of prime mover, or change the polarity of exciter by changing the connections of the field of a shunt and series machine, or one field of a compound-wound machine. Never cross the belt on a belt-driven machine unless absolutely necessary.

TABLE I—Continued

Troubles of Exciters

Symptom	Trouble	Cause	Remedy
2. Arcing of brushes	(a) Brushes not diametrically opposite	(a) Brush-holder studs loose or not set properly in first place	(a) Measure with a tape, or count commutator segments, and adjust brushes on diametrically opposite bars
	(b) Brushes not on neutral point in relation to the field	(b) Set screw holding rocker arm may have become loose or shifted through carelessness	(b) Shift rocker arm and brushes forward, or in the direction of rotation.
	(c) One or more brushes in contact with wrong number of commutator bars	(c) One or more brushes thicker than others	(c) Trim all brushes to same thickness.
	(d) Brushes cover too many bars	(d) Brushes too thick for design of exciter	(d) Use proper brushes or grind those in use to proper thickness.
	(e) Brushes out of line	(e) Brush holders not set properly on studs	(e) Adjust holders so that they line up properly.
	(f) Brushes too short	(f) Wear	(f) Replace with new ones.
	(g) Poor contact between brush and commutator	(g) (1) Oil and grit on commutator	(g) (1) Clean commutator with a dry rag. (Never use waste.)
		(2) Flint or other hard substance in brush	(2) Sandpaper the brush to remove foreign matter, keeping it in the shape of the commutator.
		(3) Brushes not trimmed properly	(3) Place a piece of sandpaper under brush with smooth side flat on commutator and work back and forth until the brush fits the commutator at all points. (Note: Do not use emery paper or cloth.)
	(h) Rough commutator	(h) (1) Vibration (2) Uneven brushes (3) Different quality of bars (4) Uneven ridges where brushes do not touch commutator	(h) If taken in time, the commutator may be trued by using a commutator stone or by a piece of sandpaper in a hollowed wooden block. Clean all copper dust from commutator before putting back in service.

TABLE I—Continued

Troubles of Exciters

Symptom	Trouble	Cause	Remedy
	(i) High commutator bars	(i) Jam nuts and cones holding segments into place, loose	(i) Carefully drive high bars back into place and tighten cones and jam nuts. Smooth commutator with stone or sandpaper.
	(j) Low bars	(j) Rough handling or wearing away due to soft bars or from a short-circuited coil	(j) Loosen jam nuts and cones and lift bars even with others if possible, and true the commutator. If bars cannot be lifted, the commutator will have to be placed in a lathe and turned even with low bars.
	(k) Loose bars	(k) Clamping cone and jam nuts, loose	(k) Tighten cone and jam nuts and true commutator.
	(l) High mica	(l) Copper wears faster than mica	(l) Undercut mica below surface of bars. Remove all dust before putting back into service.
	(m) Weak magnetic field	(m) (1) Open circuit in field (2) Short circuit in field	(m) Repair or rewind, as the case may be.
	(n) Excessive current in armature	(n) Too much load on machine	(n) Reduce the load.
	(o) Ground on machine or line	(o) Defective insulation	(o) Test and locate ground with a Megger or a magneto, cut out the grounded coil or coils, jump the defective coils if in the armature or rewind and replace them. Replace or rewind defective field coil if grounded.
	(p) Short circuit in armature	(p) Defective insulation	(p) Cut out short-circuited coil and bridge the adjacent commutator bars as a temporary measure.
	(q) Short circuit in line supplied by exciter	(q) Defective insulation	(q) Remove short circuit on line. If properly fused, a short circuit on the line will blow the fuse and protect the exciter.
	(r) Voltage too high	(r) (1) Armature speed too great (2) Armature current too great	(r) (1) Reduce speed of prime mover. (2) Cut down exciter voltage by cutting in resistance in field circuit.

TABLE I—Continued

Troubles of Exciters

Symptom	Trouble	Cause	Remedy
	(s) Commutator bars short circuited, mica worn or eaten away causing deep pits between bars	(s) (1) Copper or carbon dust between bars (2) Melted solder from leads between bars (3) Insulation between brushes and holders broken down. This also causes a ground on the machine	(s) (1) Remove foreign matter from commutator. (2) Remove foreign matter from commutator. (3) Repair insulation.
	(t) Open circuited armature coils	(t) (1) Conductor burned by short circuit (2) Connection at commutator bar becomes unsoldered by heat	(t) (1) Bridge the open circuit by connecting the commutator bars adjacent to the break or stagger the brushes in all brush holders where there are two or more in line, so as to cover the break. (2) Resolder.
	(u) Reversed armature coils	(u) Cross connection to wrong commutator bars	(u) Test polarity with a compass and connect to proper bar.
	(v) Blowholes in frame	(v) Improper casting	(v) Return machine to the factory. A trouble of this kind is hard to locate; but if all other remedies have failed, this may be the cause.
3. Rings of fire follow the brushes around the commutator	(a) Short-circuited armature coil	(a) Defective insulation	(a) Cut out short-circuited coil and bridge the adjacent commutator bars as a temporary measure.
	(b) Open-circuited armature coil	(b) (1) Conductor burned by short circuit (2) Connection at commutator bar becomes unsoldered by heat	(b) (1) Bridge the open circuit by connecting the commutator bars adjacent to the break or stagger the brushes in all brush holders where there are two or more in line, so as to cover the break. (2) Resolder
4. Flashing or excessive arcing from brush to brush	Short circuit in exciter external circuit	Usual short circuit causes	Sectionalize different parts of external circuit and test for defective circuit and repair.

TABLE I—Continued
Troubles of Exciters

Symptom	Trouble	Cause	Remedy
5. Singing of brushes	(a) Brush pressure too great	(a) Brush-holder springs not properly adjusted	(a) Remove part of the tension of the brush-holder springs. (NOTE: Brush pressure should equal 1 and 1/2 lbs. per sq. in.)
			(b) (1) Brushes too hard.
			(2) Replace brushes with ones of softer material. The use of graphite will eliminate singing. (NOTE: A small quantity of vaseline on a clean cloth rubbed on the commutator will help to reduce singing. The commutator should be wiped dry immediately after using.)
6. Chattering of brushes	(a) High bars (b) Low bars (c) Loose bars (d) High mica	(a) Jam nuts and cones holding segments into place, loose	(a) Carefully drive high bars back into place and tighten cones and jam nuts. Smooth commutator with stone or sandpaper.
		(b) Rough handling or wearing away due to soft bars or from a short-circuited coil	(b) Loosen jam nuts and cones and lift bars even with others if possible, and true the commutator. If bars cannot be lifted, the commutator will have to be placed in a lathe and turned even with low bars.
		(c) Clamping cone and jam nuts, loose	(c) Tighten cone and jam nuts and true commutator.
		(d) Copper wears faster than mica	(d) Undercut mica below surface of bars. Remove all dust before putting back into service.
	(e) Brushes set at improper angle for direction of rotation	(e) Wrong direction of rotation	(e) Reverse angle of brush setting, or change polarity of exciter and reverse rotation of prime mover.
	(f) Improper end play	(f) Shaft collars not properly set	(f) Reset collars and adjust end play. End play should not be less than $\frac{1}{16}$ inch or greater than $\frac{1}{4}$ inch.
	(g) High ridges on commutator	(g) Not enough end play	(g) Reset collars and adjust end play. End play should not be less than $\frac{1}{16}$ inch or greater than $\frac{1}{4}$ inch. Remove ridges with a commutator stone.

TABLE I—Continued

Troubles of Exciters

Symptom	Trouble	Cause	Remedy
7. Blackening of commutator at certain spots	(a) Short circuit in armature	(a) Defective insulation	(a) Cut out short-circuited coil and bridge the adjacent commutator bars as a temporary measure.
	(b) Open circuit in armature	(b) Connection at commutator bars becomes unsoldered by heat	(b) (1) Bridge the open circuit by connecting the commutator bars adjacent to the break or stagger the brushes in all brush holders where there are two or more in line, so as to cover the break. (2) Resolder.
8. Armature hot all over	(a) Overload	(a) Overload	(a) Reduce load by reducing excitation of alternator if overexcited.
	(b) Moisture in coils	(b) Operating in a damp place	(b) Dry out by running with a high load or bake in an oven.
	(c) Armature out of center between poles	(c) Bearing worn on one side	(c) Replace bearing or shim the one in use.
	(d) Eddy currents in armature core	(d) Faulty construction	(d) Rebuild core of thinner sheets or laminations. (Seldom encountered.)
9. Armature hot in spots and cool in others	(a) Short-circuited coil or coils	(a) Defective insulation	(a) Cut out short-circuited coil and bridge the adjacent commutator bars as a temporary measure.
	(b) Open-circuited coil or coils	(b) (1) Conductor burned by short circuit (2) Connection at commutator bar becomes unsoldered by heat	(b) (1) Bridge the open circuit by connecting the commutator bars adjacent to the break or stagger the brushes in all brush holders where there are two or more in line, so as to cover the break. (2) Resolder.
	(c) Reversed polarity of armature coils	(c) Cross connection	(c) Reconnect reversed coils to proper bars.
10. Armature issues a pounding sound	Armature striking or rubbing pole pieces	Bearing worn on one side	Shim the bearing or replace with a new one.

TABLE I—Continued
Troubles of Exciters

Symptom	Trouble	Cause	Remedy
11. Armature issues a loud humming sound	Path of magnetism spread out too much	Pole shoes too flat	Chamfer pole pieces so as to reduce the area of the path of the magnetic flux. Reduce the magnetic field. (NOTE: This trouble will not be encountered in a modern machine.)
12. Series field coils hot	(a) Excessive current	(a) Coils wound with too much wire, or too small wire	(a) Increase size of wire. Reduce winding or reduce current.
	(b) Moisture in coils	(b) Dampness	(b) Bake coils in an oven or by passing a light current through them.
	(c) Speed too low	(c) Prime mover speed too low	(c) Increase speed of prime mover. Increase size of driving pulley. Decrease size of driven pulley.
	(d) Partial short circuit in one or more field coils	(d) Moisture in coils	(d) Dry out coils and rewind if necessary.
	(e) Brushes not on neutral point	(e) Shifted through accident or not set properly in first place	(e) Shift rocker arm until minimum arcing takes place.
	(f) Overload	(f) Overload	(f) Reduce load.
13. Shunt field coils hot	(a) Excessive current	(a) (1) Partial short circuit	(a) (1) Test out and rewind.
		(2) Not enough turns in winding	(2) Add more turns or wind with smaller size wire, or add external resistance.
		(3) Voltage too high	(3) Decrease voltage by decreasing the speed of prime mover.
		(4) Brushes not on neutral point	(4) Shift rocker arm until minimum arcing takes place.
		(5) Moisture in coils	(5) Dry out coils and rewind if necessary.
		(6) Overload	(6) Remove part of load.

TABLE I—Continued

Troubles of Exciters

Symptom	Trouble	Cause	Remedy
14. Pole pieces hotter than field coils	(a) Eddy currents	(a) Faulty construction	(a) Replace with laminated poles if necessary.
	(b) Current through fields fluctuating	(b) Load unstable	(b) Provide field circuit with automatic regulator or if already equipped, look for trouble in regulator as outlined in voltage regulator troubles.
15. Voltage too high	(a) Speed of exciter too great	(a) Speed of prime mover too great	(a) Reduce speed of prime mover, and adjust governor so that the speed remains constant at a given load.
	(b) Field too strong	(b) Not enough resistance in series with field	(b) Cut more resistance in series with the field by means of the field rheostat.
16. Voltage too low	(a) Speed of exciter too low	(a) Speed of prime mover too low	(a) Increase speed of prime mover. Increase size of driving pulley or reduce size of driven pulley. Adjust governor.
	(b) Field too weak	(b) Too much resistance in series with the field	(b) Cut out more resistance with the field rheostat. Adjust voltage regulator.
	(c) Load on exciter too great	(c) Alternator overexcited	(c) Reduce excitation, being careful not to reduce it too much and lower the voltage of the alternator.

located, the coil leads are cut and a jumper connected across the two bars thus located. This jumper completes the circuit through the armature, which should be tested again before putting it back into service.

With a single series winding, owing to the manner in which the leads are connected to the commutator (the winding is two-circuit), the method of jumping a defective coil is different from that of a single parallel winding. In this type of winding, the defective or short-circuited coil is cut as in the former case; but in locating the commutator bars to which the coil connects, it will be found that they are on opposite sides of the commutator, that is, directly opposite each other. If adjacent bars are connected in a case of this kind, two such jumpers are required and a perfectly good coil short circuited unless it is also cut. The proper method of jumping the defective coil is shown in Fig. 3.

Repairing open circuits in exciter armature windings

An open circuit in a parallel winding is indicated by flashing of the brushes at one spot only on the commutator, since the circuit is broken when the brushes pass the break at every revolution. With a parallel winding, the commutator bars to which the defective coil connects can be readily located by their burned or blackened appearance. To repair, connect a jumper between the two bars which are blackened. It is also best to cut the leads off at the bars to eliminate any chance of the open-circuited coil closing due to centrifugal force. The armature should be tested with a magneto before putting it back into service. The method of repairing an open circuit in a parallel winding is shown in Fig. 4.

In using the apparatus shown in the diagram, brushes are located on opposite sides of the commutator, as on segments *4* and *10*, with a bank of lamps connected in series with the supply voltage. The current flowing through the windings is adjusted to give normal deflection on the meter. In making the test with the voltmeter leads connected to segments *11* and *12*, as shown in the diagram, normal deflection of the voltmeter needle will result. With the voltmeter leads connected to segments *5* and *6*, *7* and *8*, or *8* and *9*, there will be no deflection of the voltmeter needle. With the voltmeter leads connected to segments *6* and *7*, or to those segments to which the

open-circuited coil was originally connected, current will flow from the brush on segment *4* through coils *4*, *5*, and *6*, thence through the meter and through the coils connected to segments *7*, *8*, *9*, and *10* to the brush on segment *10*. The resistance of the meter being many times greater than the resistance of the armature windings, practically full voltage between the brushes will be indicated by the meter. If the open circuit does not occur in the leads from the winding to the commutator and it cannot be located, the assumption is that the

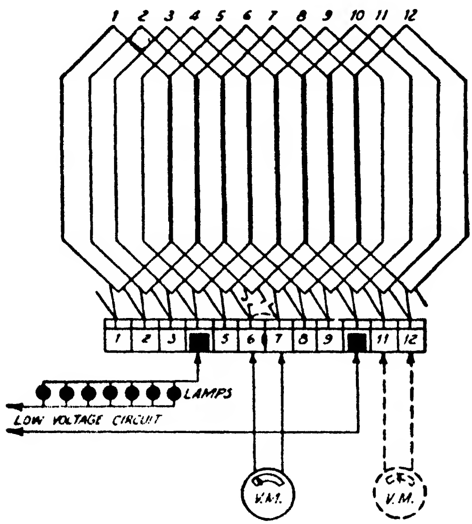


Fig. 4. Connections for Testing for Open-Circuit in a Parallel Winding

break is somewhere in the slots. If this happens to be the case, the two leads should be cut as shown in the diagram and taped so that they cannot come together and a jumper connected as shown by the dotted line between *6* and *7*.

Where an open circuit occurs in a series winding, one-half of the coils are dead and the exciter will not build up. Unlike a parallel winding, the commutator bars cannot be found at a glance but must be located by testing. In testing for an open circuit in a series winding, the apparatus required and the diagram of connections both for the test and the method of repairing are shown in Fig. 5. The same equipment is used for this test as is used for a parallel winding, only

the results of the tests are different. With supply voltage on the brushes and the voltmeter leads connected to bars *5* and *6*, the meter will be violently deflected, since all the voltage in one-half the winding is impressed on the meter. The same effect is obtained if the meter leads are connected to bars *11* and *12*.

In repairing an open circuit in a series winding, one jumper only is necessary. If jumpers are connected on opposite sides of the commutator where the leads of the defective coil are located, the

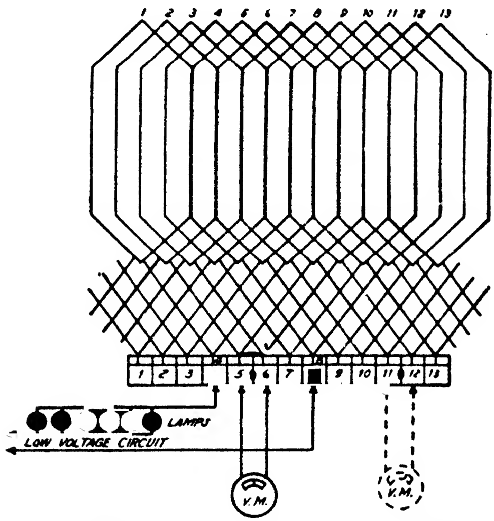


Fig. 5. Testing for Open Circuit in a Series Armature Winding

coils adjacent to the break will be paralleled and will consequently heat up, since double voltage will be impressed on them, and they will not only carry their normal current but a circulating current which will flow between them.

Locating a ground in armature winding and repairing it

A ground in an armature winding may be caused from various reasons but all grounds are due to one particular thing, **defective insulation.** A ground in an armature coil is usually caused from poor insulation and stresses caused by magnetic induction and centrifugal force. Another cause, which while an insulation breakdown, is due

primarily to poor workmanship. If the slots in the armature core are properly insulated and care is taken in inserting the coils, there is not much danger from a ground. Water is another good cause for a ground, and it is for this reason that an exciter must be located where there is little possibility of damage from moisture.

A ground in the commutator may be due to rough usage, a short circuit or an open circuit, loose clamping rings, etc. The cones which clamp the commutator to the shaft are insulated from the commutator with sheets of mica and if the clamping ring becomes loose, the mica is liable to shift and allow the segments to come in contact with the cones. Other causes are high voltage, oil and dirt, or failure of the insulation back of the ring.

In order to better locate a ground in either an armature coil or a commutator, the windings and bars must be divided into sections by removing the leads from the commutator. Each section is then tested by means of a lamp in series with a low voltage circuit, one end of the test set being permanently connected to the shaft while the other end is successively touched to various sections of the commutator and windings.

When the faulty section is located, the leads of all coils in this section are disconnected from the commutator and each coil and segment tested separately. After the ground is located, if in a coil, the coil is either removed or cut out of circuit as outlined and illustrated under the heading of repairing short circuits and open circuits for series and parallel windings.

When testing for a ground with a voltmeter, the grounded segment will give a smaller reading than a normal segment or coil.

Open circuit in a field winding

An open circuit in either a series or a shunt field may be caused by the connections becoming loose through vibration or rough handling. An open circuit in the fields of a shunt-wound exciter will not allow the machine to build up, nor will a compound-wound exciter build up if the shunt field is open. A compound-wound exciter will build up, however, if the series field is open, the machine then having the characteristics of a shunt-wound exciter although there will be no current or voltage in the external circuit of the exciter. This is illustrated in Fig. 6.

To locate an open circuit in either field, the field coils are all disconnected from the armature circuit and each coil tested separately with a voltmeter. Low voltage, either direct or alternating, is impressed on the outside terminals of the field with the coils still con-

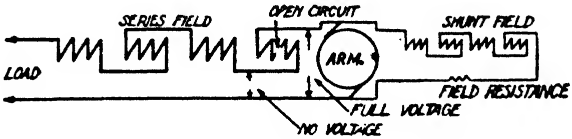


Fig. 6. Wiring Diagram of Field and Armature Circuits

nected in series and the voltmeter leads connected to the terminals of each coil in succession, as shown in Fig. 7. An open-circuited coil will give full deflection of the meter needle, since it forms a path for the voltage, while a coil which is not open-circuited will give no deflection on the meter.

When located, the defective coil is either rewound or replaced with a new one.

Short circuit in a field coil

A short-circuited field coil, either series or shunt, may be caused:

(1) By the leads coming in contact with one another

(2) By the insulation breaking down between two turns in different parts of the coil

(3) By moisture in the coil

(4) By grounds

The first will completely short circuit the coil; the second will only partially short circuit the coil; while the third and fourth may

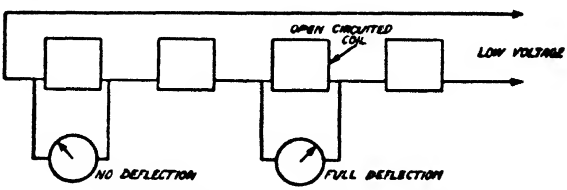


Fig. 7. Testing Field Coils for Open Circuit

do either, depending on the number of grounds and the amount of moisture.

A short-circuited field coil is easily located by means of a voltmeter, the same procedure being followed as in locating an open

circuit. The results of the short-circuit test differ from those of an open-circuit test, since the voltmeter will give a zero reading across a coil that is completely short circuited. If only partially short circuited, the reading will be somewhere between zero and that across a good coil. The voltage across any coil not short circuited is equal to the line voltage divided by the number of coils connected in series. For instance, if there are four coils in the field and the line voltage is 120, there will be a reading of 30 volts across each coil. If, however, one coil is totally short circuited, there will be no reading across it; but across each of the others there will be a reading of $120 \div 3 = 40$ volts. The remaining coils will therefore become hot while the short-circuited coil will remain cold.

Troubles of interpole field coils

On exciters equipped with interpoles, the troubles due to short and open circuit are the same as in the series field. The interpole coils are connected in series with the series field and armature and the brushes on this type of machine are in the exact center of the interpole field coils.

Methods of operating an exciter under-compounded, over-compounded, and flat-compounded

An under-compounded machine is one in which the voltage varies with the load, that is, with an increase in load the voltage will decrease. An over-compounded machine is one in which the voltage increases as the load increases. A flat-compounded machine is one in which the voltage remains stationary under varying conditions of load.

To under-compound a compound-wound exciter or a shunt-wound exciter, either with or without interpoles; shift the brushes in the direction of rotation but do not shift them too far or they will arc and burn the commutator. Another way to under-compound an exciter is to shunt either the series or interpole fields or both by means of diverters or shunts. Decreasing the number of turns in the series field will cause the exciter to be under-compounded; while increasing the number of turns in the series field will cause the exciter to be over-compounded. Since it is possible to reduce the compounding, that is, under-compound an exciter by means of shunts, most compound-wound exciters have their series field coils

wound with an extra turn or so; in other words, they are over-compounded.

The use of shunts or diverters as they are usually called is to provide against an increase in voltage with an increase in current. It is for the same reason that exciters for alternators are also equipped with diverters, that is, to maintain a constant voltage to the alternator fields regardless of the exciter load. A diagram of connections showing the method of connecting the diverters in the series and interpole fields of a compound-wound exciter is shown in Fig. 8.

The diverters are here shown connected through disconnecting switches which may be opened and closed to obtain any amount of

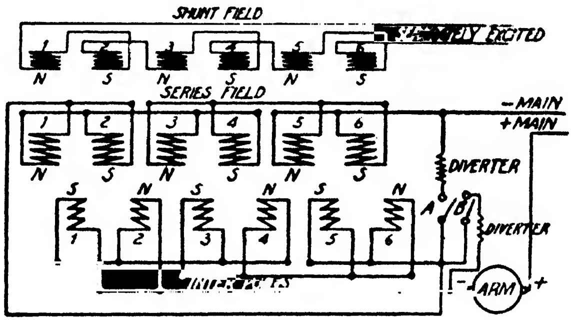


Fig. 8 Wiring Diagram of a Separately Excited Compound-Wound Interpole Exciter

compounding. When these switches are open, the machine is over-compounded; when these switches are closed, the machine is either flat-compounded or under-compounded, depending on the amount of resistance in parallel with the series and interpole fields. The positions of switches *A* and *B* in the diagram are for operating the machine over-compounded. The two switches are open and the diverters are cut out of circuit. For ordinary flat-compound operation, diverter switch *A* is closed and switch *B* is open; while for greater flat-compounding, that is, for a greater variation in load with a constant voltage, switch *B* is also closed, thus diverting some of the armature current from the interpole field.

For ordinary flat-compounding all of the armature current flows through the interpole field but not all of it flows through the series

field since the diverter circuit to which switch *A* connects is in parallel with the series field and therefore the current is divided—part flowing through the diverter and part through the series field. The diverters or shunts consist of German silver of various thicknesses and amount of resistance.

Another method of connecting and arranging the diverters in the series and interpole field circuits is shown in Fig. 9. Here, a

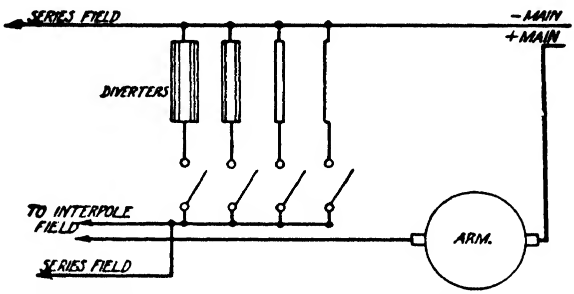


Fig. 9. Switches for Changing Amount of Compounding of Exciter

series of switches are shown, and all of the circuits are paralleled. These diverters supply the necessary compounding to maintain a practically constant voltage, under varying load conditions, by closing those that experience shows are the most effective.

CARE AND MAINTENANCE OF VOLTAGE REGULATORS

Voltage regulators are of several types but their main functions, are all the same, namely, to regulate either manually or automatically the exciter voltage to the alternator fields and to regulate the alternator voltage under varying conditions of load.

Automatic regulators of both the contact-making, vibrating, and induction types are used in conjunction with hand-regulated and motor-regulated field rheostats. As the contact-making and vibrating types have the greatest field of usefulness, the following applies to them only.

Operating instructions for voltage regulators

In order that a vibrating or a contact-making regulator may function properly, the following instructions are given.

(1) Keep the regulator contacts and other mechanism absolutely clean. The relay contacts should be filed or sandpapered once a week, while the main regulator contacts should be sandpapered at least once a month.

(2) Where the regulator controls one alternator and exciter, the alternator main field rheostat should have all the resistance cut out. If part of the resistance is left in the alternator field, there will be considerable heat losses in the rheostat and the regulator in trying to function properly will tend to raise the exciter voltage, which will impose a heavy duty on the regulator contacts.

(3) Where one regulator controls two or more alternators in parallel which have different characteristics, the alternator operating at the lowest power factor should have some resistance left in its field rheostat, the one operating at the highest power factor should have all resistance cut out, and those operating at power factor values between the highest and lowest should be graded so that they all operate at the same power factor.

(4) If the regulator does not respond quickly, quicker response may be had by paralleling the exciter field coils. For either 125-volt or 250-volt exciters, there should be enough external field resistance to reduce the voltage by four-fifths in less than eight seconds. The point on the exciter field rheostat which gives one-fifth voltage is the operating point and should be marked so that the contact arm can always be set at this point while the exciter voltage is under regulator control.

(5) Exciters which are to be regulator controlled and which are to be also paralleled should be slightly under-compounded, that is, the voltage of these exciters should drop when the current in their external circuits increases. In order to increase the value of under-compounding, the exciter brushes should be moved forward in the direction of rotation, but not enough to cause arcing between the brushes and commutator.

Troubles of voltage regulators

The troubles of voltage regulators are so closely allied to those of the alternators and exciters which they link and serve that one should be thoroughly familiar with the troubles of alternators and exciters in order to more fully understand those of voltage regulators. The usual troubles of voltage regulators are found in Table II.

CARE AND MAINTENANCE OF POWER TRANSFORMERS

After the installation of a transformer or a bank of transformers and before the final connections are made, all parts should be thoroughly inspected and tested for moisture, polarity, ratio, etc.

Drying out a transformer

If moisture is present in a transformer, it will usually be indicated by the presence of rust inside the tank. Transformers that do not use oil as a cooling medium as well as those that use oil but are

TABLE II

Troubles of Voltage Regulators

Symptom	Trouble	Cause	Remedy
1. Relay contacts burn, pit, or blacken quickly	(a) Contacts offer too much resistance and do not make proper contact	(a) Contacts not made of proper material	(a) If contacts are not silver tipped, they should be replaced, since silver-tipped contacts have a low resistance and make positive contact.
	(b) Contacts arc when opening and closing	(b) (1) Not enough condensers in shunt or parallel with the contacts	(b) (1) If the condenser is not open circuited, connect another in parallel with the existing condenser.
		(2) Open circuit through condenser	(2) Test out condenser by applying a low voltage on its terminals and then discharging it through a lamp. If open circuited, insert a new one. (NOTE: Each set of relay contacts has a condenser in parallel to decrease the arcing. When the relay contacts open the condensers are charged; and when the relay contacts close, the condensers discharge through the contacts.) Relay contacts should be filed and cleaned once a week to assure proper functioning. After cleaning, the contacts should be adjusted so that there is a gap of $\frac{1}{32}''$ between them. To prolong the life of the contacts, their polarity should be reversed once a day. The polarity of the contacts is reversed by reversing the reversing switches at the bottom of the regulator.
2. Alternator voltage varies when the load changes	Exciter voltage varies	(a) (1) Main contacts arcing or not closed properly (2) Main contacts too close together	(a) (1 and 2) Clean the main contacts with a fine file or carborundum stone and see that they make a perfect fit. Adjust the contacts by means of the gauge blocks. The levers should rest on these blocks and the contacts should just touch each other.
		(b) Limit pins in contact with the lever	(b) These pins are for adjusting the minimum and maximum regulated exciter voltage and should in no case come in contact with the lever.

TABLE II—Continued

Troubles of Voltage Regulators

Symptom	Trouble	Cause	Remedy
		(c) Dashpot piston either sluggish or too quick in action NOTE: There are other causes for the symptom just discussed, but the causes due to troubles of voltage regulators are fully covered. For other causes, the student is referred to alternator troubles.	(c) If sluggish, the oil is either too thick or the dashpot mechanism is out of adjustment. Change the oil and adjust the piston so that it is about midway between the port holes. If the piston has a tendency to pump it moves too freely and a heavier grade of oil should be used.
3. Regulator contacts stay in one position	Open circuit in regulator circuit	Either the D.C. or A.C. coil is burned out or the connections broken	Test out each coil with a magneto or lamp and low voltage circuit and replace the coil affected.
4. Regulator does not respond quickly	Exciter does not respond	(a) Too much resistance in exciter field circuit	(a) (1) Cut out some of the resistance in the exciter field rheostat. (2) Parallel the exciter field coils.
		(b) Exciter overcompounded	(b) Move the exciter brushes in the direction of rotation, but not enough to cause arcing.
5. One or more alternators operate at low power factor	Too much wattless current	Too much resistance cut out of alternator field rheostat	Cut some resistance in the field rheostats of alternators which are paralleled with others operating at a higher power factor.

shipped in a dry state, especially if the voltage is greater than 2200 volts, should be thoroughly dried out before going into service.

Probably the best method of drying a transformer is to force a current of dry air at a temperature of 90 degrees centigrade (194 degrees Fahrenheit) through and around the windings for not less than 24 hours. For high voltage transformers, the time should be extended to from 72 to 96 hours, depending on the voltage and capacity.

Another method of drying, but one that must be used with care, is to short circuit one winding (usually the low voltage winding) and impress not more than 5 per cent (2 per cent is better) of the voltage for which it is designed, on the other winding (usually the high voltage winding). With a voltage 2 per cent of the normal voltage impressed on the high-voltage winding and the low-voltage winding short circuited, a current of about 33 per cent of normal full load current will flow through the two windings. The current should be adjusted so that the temperature will not exceed 80 degrees centigrade (176 degrees Fahrenheit) at the hottest spot. Thermometers must be placed at various points in the transformer air ducts through the core and in both windings.

Treatment of transformer oil

Transformers built for voltages exceeding 2200 volts are usually shipped with the tanks filled with oil in order that no moisture may get to the core and windings during transit. If the tank tops are properly sealed, there is little chance of moisture getting into the tank, but the oil should be tested before connecting to the line as 0.1 per cent of moisture will render the oil unfit for service.

There are several methods of determining the presence of moisture in oil. The quickest method is to immerse a red hot piece of steel into a sample of oil taken from the bottom of the tank. The presence of moisture will be denoted by a hissing sound.

Another method and one which is more reliable is to drop pieces of copper sulphate which has been heated enough to turn it white into several samples of oil taken from the bottom of the tank. If the chemical turns blue or its natural color, it denotes the presence of moisture.

The surest method, if the voltage and apparatus are available,

is to impress 40,000 volts across two ½-inch disks suspended in the oil and spaced ⅕-inch apart. If no arc is formed, the oil may be considered in good condition. If, however, the film breaks down, the oil should be treated as described below.

Removing moisture from oil is a slow and tedious process. There are several methods which are given in the order of their importance, the last method being the best and most important.

Gravity method. With the gravity method, the oil should be allowed to stand undisturbed from a week to ten days and then siphoned from the top into clean containers until within a foot of the bottom. The next eight inches, or within four inches of the bottom of the tank, should be put in separate containers for further treatment, while the balance should be thrown away.

Centrifugal treatment. With this method, the oil is placed in a separator after the principle of a cream separator. This operation should be performed at least three or four times.

Chemical treatment. Certain chemicals have a great affinity for moisture and have the ability of extracting it from oil. The most important of these dehydrating chemicals are calcium chloride, calcium oxide, calcium carbide, and metallic sodium, the first mentioned being the quicker in action. A quantity of the chemical is placed in the oil, in the proportion of 6 parts chemical to 100 parts of oil by weight, and allowed to stand for four or five days and then filtered from the oil.

Heat treatment. The oil is heated to the boiling point, or 100 degrees centigrade (212 degrees Fahrenheit) and all pressure removed. In this manner the moisture is evaporated. Care must be exercised that the heat does not exceed 105 degrees centigrade, as the oil will be ruined. The heat should be applied for at least twenty-four hours to be effective.

Paper filter treatment. This method is better by far than those preceding as the transformer need not be taken out of service; while with those mentioned above, it has to be out of service. The filter press consists of a high-pressure pump and a stack consisting of several layers of blotting paper. The oil is drawn from the bottom of the transformer tank and forced by the pump through the blotting paper stack back into the top of the tank. All of the moisture is absorbed by the blotting paper, which has to be changed from time

to time depending on the amount of moisture in the oil. Some filter presses are equipped with heated coils through which the oil passes before going back into the tank.

NOTE: In all the methods except the last mentioned, the oil should be tested before putting the transformer back in service.

Transformer polarity tests

Polarity tests between leads of the windings of one transformer are made by connecting two adjacent primary and secondary leads

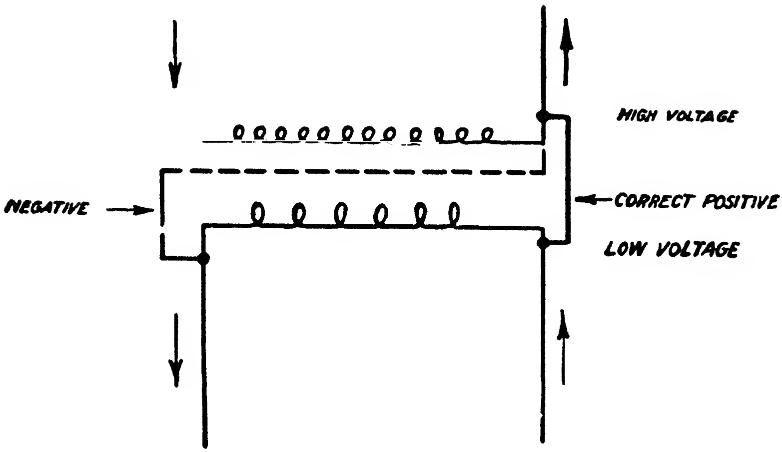


Fig. 10. Direction of Transformer Voltages

together and noting whether the secondary voltage is added to the primary voltage or is subtracted from it. Where the two voltages add up, the polarity is positive; and where they subtract from each other, the polarity is negative. Fig. 10 shows the direction of primary and secondary voltages in their proper relationship where the polarity is positive, while Fig. 11 shows two transformers paralleled where one has positive polarity and the other has negative polarity. These transformers cannot be paralleled and operated when connected in this manner, but can be operated in parallel when connected as shown in Fig. 12.

In paralleling transformers, the polarities should be tested before connecting. This test can be made by a voltmeter or by placing a fuse between the secondaries. If when tested with a voltmeter

the voltages of both primaries and secondaries of all transformers add up, the polarity is correct and paralleling can be proceeded with. The connections for a voltmeter test are shown in Fig. 13. The

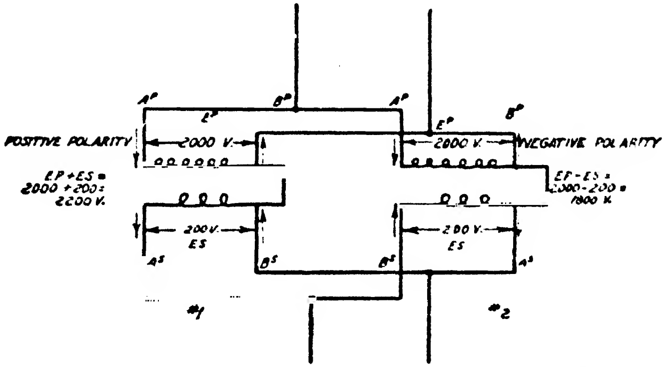


Fig. 11. Direction of Transformer Voltages When Transformers of Opposite Polarity Are Paralleled

voltmeter is first connected across the high-tension winding at *V1*, then across the low-tension winding at *V2*, and lastly at *V3*. If

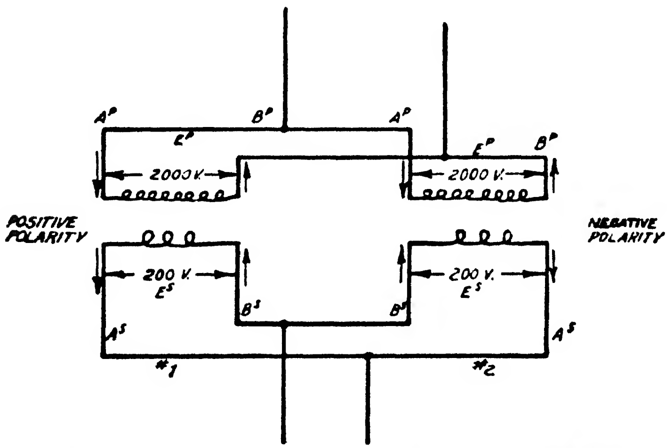


Fig. 12. Correct Method of Connecting a Transformer with Positive and Negative Polarity in Parallel

the voltage at *V3* is the sum of *V1* and *V2*, the polarity is correct. If, on the other hand, all the voltages subtract, the polarity is also correct and the transformers may be paralleled.

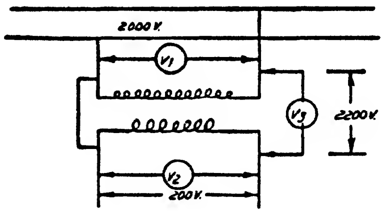


Fig. 13. Method of Making Transformer Polarity Tests

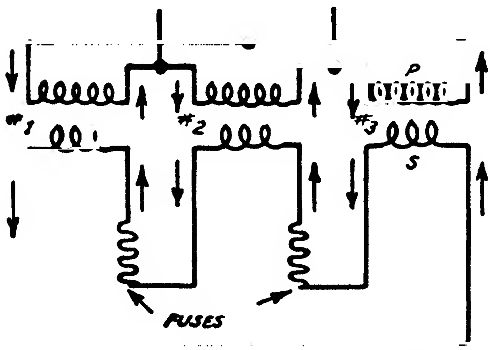


Fig. 14. Direction of Voltages and Method of Testing Polarity with Fuses

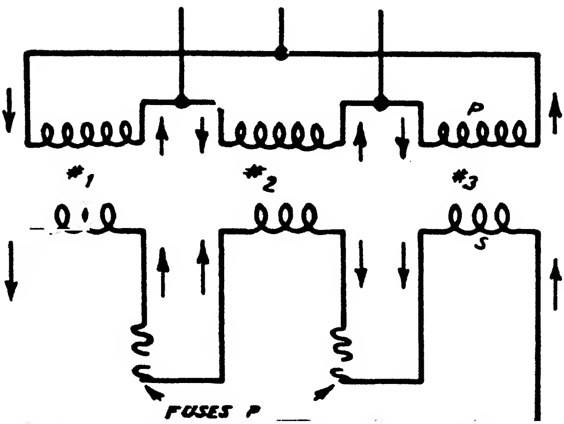


Fig. 15. Direction of Voltages with Polarity of Transformer 2 Reversed

When testing by means of a fuse, the primaries are first paralleled and then the secondaries are paralleled with a fuse in series in all lines but one. If any of the fuses blow, it will indicate wrong polarity.

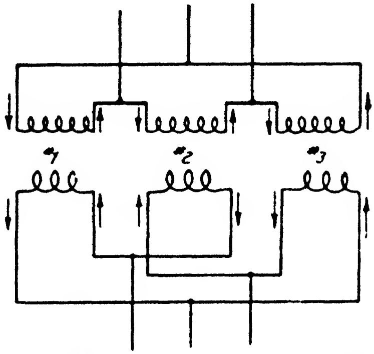


Fig. 16. Proper Method of Connecting Transformer 2, Which Has Reversed Polarity

Switching the connections around until none of the fuses blow will indicate correct polarity. This is illustrated in the following diagrams. Fig. 14 shows three single-phase transformers connected in delta with the polarity of each correct. Fig. 15 shows the polarity

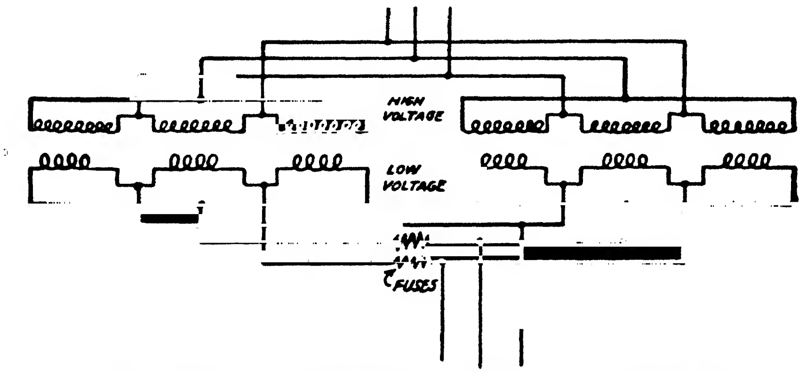


Fig. 17. Method of Testing Two Banks of Transformers before Paralleling Them

of No. 2 transformer reversed, while Fig. 16 shows the proper connection for Fig. 15 with No. 2 transformer apparently reversed. Fig. 17 illustrates the method of testing two banks of single-phase transformers for parallel operation.

Transformer ratio tests

Ratio tests are made by impressing a fraction of the normal voltage on the transformer windings and the ratios of the tap voltages are measured with a voltmeter. The ratios of primary and secondary voltages are obtained in the same manner or by balancing against a standard of known ratio. Fig. 18 illustrates the connection of the apparatus for a ratio test.

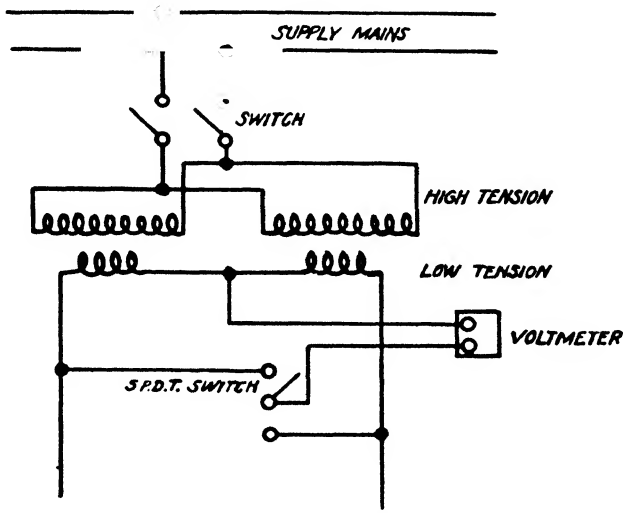


Fig. 18. Connections for Transformer Ratio Test

Fig. 19 shows the effect of connecting two transformers of different ratio in parallel. Where two such transformers are paralleled, circulating currents will result. For instance, in Fig. 19 No. 1 transformer has a ratio of 10-1, while No. 2 has a ratio of 9-1. The core loss of No. 2 is approximately 10 per cent higher than that of No. 1, since the circulation of full-load current is increased 110 – 100, or 10 per cent. If each transformer has a capacity of 110 kilovolt-amperes at the specified voltage and both are the same ratio, 1000 amperes will flow through the secondaries of each at unity power factor; but since the ratios are different, the impedances of the secondaries are also different. The impedances with equal ratios equal 110 ÷ 1000, or .11 ohms. The impedance, however, of No. 2 is less than that of No. 1, since there are less turns in the secondary. From Ohm's law, the current

flowing in No. 1 equals 110000÷110, or 1000 amperes, while the current in No. 2 equals 110000÷122, or 901 amperes. When the two transformers are connected in parallel, however, the winding having the least impedance will carry the greatest current, so that No. 1 will carry 901 amperes and No. 2 will carry 1000 amperes, and the impedances of the two will be equal, since 110÷901 equals .122 ohms and 122÷1000 equals .122 ohms. The 12.2 volts shown in the diagram, which is the difference between the two secondary voltages, is the real cause of the circulating current, since it forces the current against the impedance of the windings, the circulating

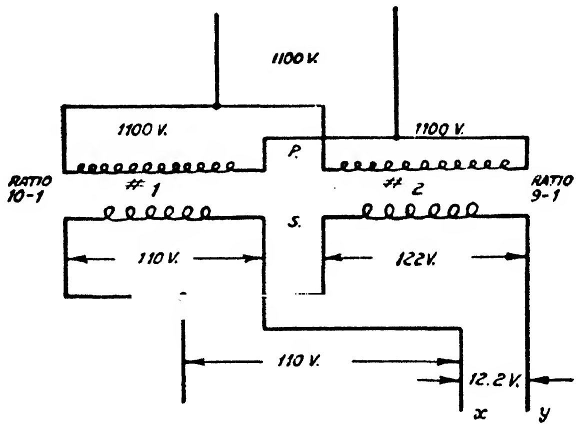


Fig. 19. Voltage Obtained When Attempting to Parallel Transformers of Different Ratios

current really amounting to 1000−901, or 99 amperes. It is therefore always advisable when paralleling transformers to measure the voltage between the points as represented by x and y in the diagram. If no voltage is shown between these points, the transformers have the same ratio and no trouble will be caused from circulating currents.

Precautions for filling transformer tank with oil

If for any reason the oil in a transformer tank becomes jellied or worthless due to overheating or other causes, the oil should be removed and the tank should be thoroughly flushed out, and every precaution should be taken that no foreign matter remains in it. When filling the tank, the oil should be strained through at least four

layers of cheese cloth in order to remove all impurities. The presence of water will be readily noticed by the formation of globules in the oil on the cloth.

CAUTION: Never use rubber tubing to convey oil to the tanks, as there is always a certain amount of sulphur in the rubber which is injurious to the insulation of the transformer windings.

In all cases the oil should be allowed to settle for at least twelve hours before putting the transformer into service. In any transformer the oil level should be well above the windings and core; while in transformers equipped with oil gauges, the level should be about half the height of the gauge when cold, in order to allow for expansion when the oil becomes warm due to service. As the insulation absorbs a slight amount of the oil, the oil level should be noted two or three days after filling. As soon after filling as possible, the covers should be placed on the tanks in order that no moisture or other foreign matter may get into the tanks.

Precautions for a water-cooled transformer

Before impressing voltage on water-cooled transformers, the water should be applied at low pressure in order to determine if there are any leaks in the cooling coils. The water pressure should not be left on for any length of time, however, as the tubes might sweat—the same as any water pipe will do in the summer time. In no case should the temperature of the oil fall below 10 degrees centigrade (50 degrees Fahrenheit).

Precautions for an air-blast transformer

Before impressing voltage on air-cooled transformers, the blowers should be run a short time only, in order to ascertain that none of the ducts are clogged and that the air pressure is equally distributed. The air pressure should not be left on without voltage being impressed on the windings, since air always contains a certain amount of moisture which is detrimental to the insulation of the windings. Air-blast transformers should never be placed where there is any liability of water dripping into them, as they are usually open at the top. For this reason no water pipes should be installed over or around them.

It is usual to bring both primary and secondary leads out of the bottom of an air-blast transformer, the cables being run in the air

duct—the air current thus keeping them cool and increasing their carrying capacity.

Continuity of service

Owing to the importance of transformers in a transmission system, they should be installed in such a manner that a unit can be

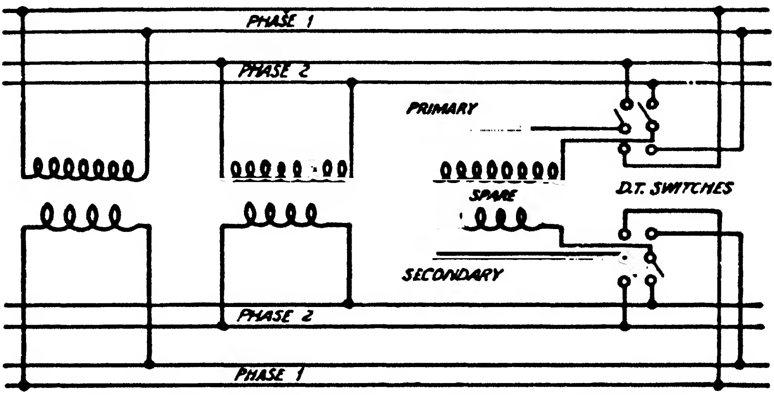


Fig. 20. Diagram of Spare Transformer Connections on a 2-Phase System

cut out of service in the event of trouble without tying up the remainder of the system for any length of time. On any installation

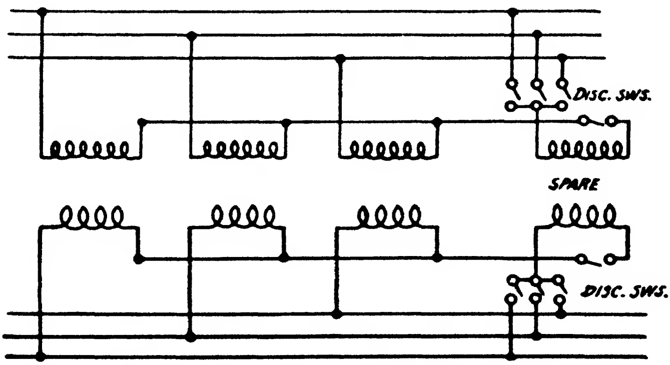


Fig. 21. Diagram of Spare Transformer Connections on a Star-Star Transformer Bank

where continuity of service is of prime importance, both high-voltage and low-voltage windings should be equipped with disconnecting

switches. In some cases service is so important that spare units are installed and connected ready for immediate use. Fig. 20 illustrates the connections of a spare unit in a two-phase system. The spare unit has both high-voltage and low-voltage windings connected to double-throw switches in such a manner that no matter which of the working units becomes disabled, the spare is immediately available.

Fig. 21 shows the connections of a spare unit in connection with three single phase transformers connected star-star on a three-phase system, while Fig. 22 shows the same for a delta-delta connected bank. With three-phase banks connected delta-delta, 58 per cent

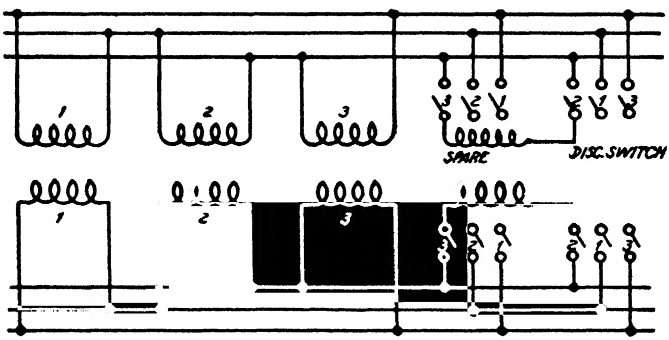


Fig. 22. Diagram of Spare Transformer Connections on a Delta-Delta Transformer Bank

of the total capacity of the three transformers can be carried indefinitely with two of the units operating on open delta.

CAUTION: No transformer should be allowed to exceed a temperature of 80 degrees centigrade (176 degrees Fahrenheit).

Troubles of transformers

Owing to the fact that transformers are of rugged construction and have no moving parts, if they are properly protected on the high-voltage side by circuit breakers and lightning arresters and on the low-voltage side by circuit breakers and fuses, they should give little or no trouble. Insulation breakdown and breakdown of high tension bushings and terminals might be encountered. The usual troubles and their remedies are given in Table III.

Insulation breakdown. This may be caused in a number of ways, such as:

(1) Line surges
(2) Lightning
(3) Electromagnetic stresses
(4) Faults of cooling medium
(5) Short circuits
(6) Switching on and off of heavy loads
(7) Insufficient insulation between layers and between the various sections of the two windings
(8) Operating at too low a temperature
(9) Electrostatic capacity too great
(10) Oscillation of line conductor
(11) Overloads
(12) Variation in generator speed and voltage
(13) Unequal division of load
(14) Voltage strain
(15) Wrong polarity
(16) Grounds

A safeguard against a considerable number of these causes—as Nos. 1, 2, 5, 10, 11, 14, 15, and 16—is proper protection by the installation of choke coils, lightning arresters, and circuit breakers with relay protection.

For cause No. 3, which is due either to faulty design or to the windings not being properly braced so that they shift and cut the insulation on the core, the only remedy is in reinforcing the bracing.

The remedy for No. 4 is in the periodical inspection of the cooling medium, whether oil, air, or water, or combinations of these, and the removal of the cause—such as an obstruction in the cooling tubes of a water-cooled transformer, an obstruction in the oil pipes of a forced oil-cooled transformer, or an obstruction in the air ducts of an air-cooled transformer.

Cause No. 5 is probably the cause of the greatest number of transformer failures and may be due to several of the other named causes. A short circuit of short duration may not do much damage, but if it is allowed to remain with the voltage impressed on the windings, a current several times greater than full load current will flow in the windings and burn them out. A short circuit in the windings of one of the units of a three-phase bank of transformers will increase the voltage across the two lines adjacent to the short circuit by the $\sqrt{3}$, as shown in Fig. 23. This diagram illustrates a

bank of step-up transformers connected star on the low-voltage side and delta on the high-voltage side. The result of the short circuit is that the phase displacement is changed from 60 degrees to 120 degrees, as shown by the vectors, and the two outside transformers are connected in reversed open delta.

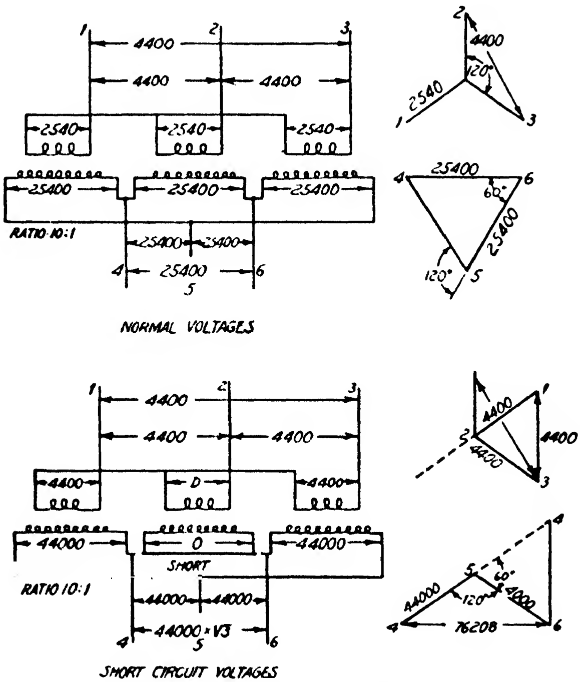


Fig. 23. Transformer Voltages Obtained with One Transformer Short Circuited

The only remedy for cause No. 6 is in switching part of the load at a time on or off.

Cause No. 7 is caused by faulty construction and the remedy is entirely up to the designer. This fault, however, seldom occurs in the field, since all apparatus is usually given a severe test before leaving the factory.

In regard to cause No. 8, where a transformer is operated at a low temperature, "breathing" is prevalent. A transformer will not breathe or sweat if operated at a temperature not lower than 10 degrees centigrade.

Cause No. 9 is due to condenser effect, either between adjacent coils, adjacent layers, between high- and low-voltage windings, or between the windings and ground. The remedy for this cause is to stabilize the effect by introducing static or rotary condensers into the system.

The remedy for cause No. 12 is in properly governing the speed of the prime mover.

Cause No. 13 is due to unequal voltage in the various units of a bank of transformers. If the taps are too high in one of the units, the voltage of that unit will be greater than in the others, with the consequence that the current will also be greater, and thus this unit will carry a greater proportion of the load.

Where two or more banks of transformers are paralleled, if the reactance of the various banks is not the same, the bank or banks having low reactance will carry more load than their capacities will allow. Introducing more reactance in the low-reactance bank or banks will remedy this fault. Fig. 24 shows the connections for paralleling two banks of transformers having different values of reactance. The reactances are connected in the low voltage delta of the low reactance bank.

In regard to cause No. 14, it might be added that the voltage strain between high- and low-voltage windings is equal to the sum of the two voltages, but since the sum of the two seldom exceeds the breakdown voltage test applied to the transformer, a breakdown from this cause alone is seldom encountered, providing the normal primary voltage is not exceeded. If, however, the primary voltage is exceeded through the crossing of the primary lines with other lines carrying higher voltage, the effects may be disastrous.

In regard to cause No. 15, if two transformers are connected with their polarities reversed, the one will buck the other, i. e., they are both practically short circuited and the result is the windings will become roasted and ruined in a very short time unless remedied.

Next to cause No. 5, cause No. 16 is the cause of the greatest number of transformer failures. Where the neutral is grounded on a star-connected three-phase bank, a ground on any of the phases short circuits the windings and puts the entire bank out of commission. With the star connection, the voltage between the windings and core is 57.7 per cent of the impressed line voltage. The insulation

of the windings need not be greater than 57.7 per cent of that required for full line voltage but most manufacturers insulate for full line voltage, since it makes the transformer adaptable for other connections.

With the neutral ungrounded on a star-connected bank, the voltage from line to ground is normally 57.7 per cent of the line voltage, but with one line grounded, the neutral is liable to shift, with the result that the voltage between the ungrounded lines and

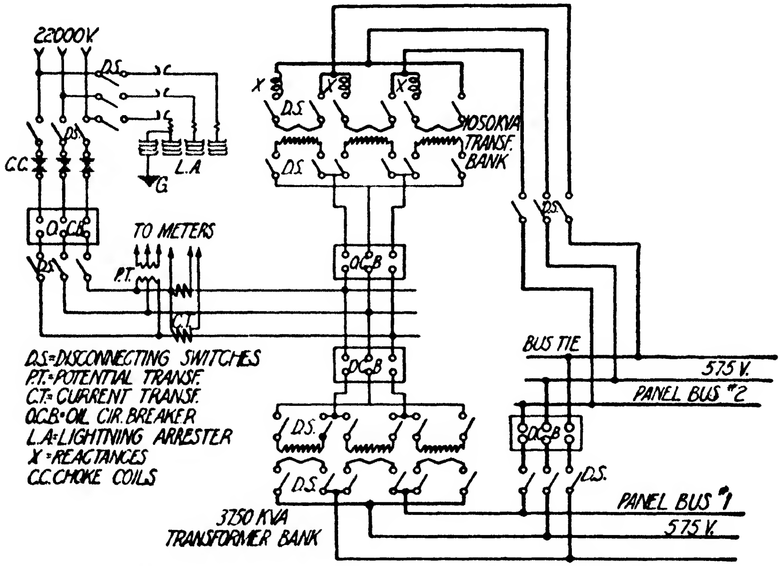


Fig. 24. Diagram of Connections for Paralleling Two Transformer Banks

ground is increased to full-line voltage. The unbalance thus caused results in unequal heating of the various units and disturbance to the secondary network.

With a ground on a delta-delta bank, the maximum insulation stress to ground is the normal line voltage. When the middle point of one transformer only is grounded, the difference in potential between this point and the phases next to the grounded phase is one-half the line voltage, while that in the remaining phases is one-half voltage times $\sqrt{3}$.

The maximum voltage strain in the case of a ground on either phase of a two-phase system on the high-voltage side in a four-wire

distribution is exactly the line voltage, but a ground on either line and a short circuit between two phases may cause insulation stresses equal to line voltage times $\sqrt{2}$.

With two-phase three-wire distribution, the maximum voltage strain in the event of a ground on the low-voltage windings is the low voltage times $\sqrt{2}$. If the middle wire is grounded, the voltage is limited to the low-tension voltage only.

Breakdown of high-voltage bushings. This may be caused from faulty construction of the bushing, from moisture, or other foreign matter. If a bushing becomes cracked, particles of dust may enter the break and form a path to the transformer case. If moisture is allowed to gather on a bushing the same thing may happen. If the oil level is allowed to become low, so that the terminal board is exposed, a path may be formed through carbonization of the board if constructed of wood, or the presence of moisture may cause a path if built of any other material. Care should be exercised that the terminal boards are perfectly clean before putting a transformer into service, and the oil level should never be allowed to a level where the board is exposed, where the transformer is an oil-cooled or oil-insulated type.

CARE AND MAINTENANCE OF RELAYS

The various uses to which relays can be put make them one of the greatest links in the chain of hydroelectric equipment, and on the proper functions of these relays depends the continuity of service which a hydro plant can give.

In order to protect properly a hydro system by means of relays, the following are the main considerations:

(1) To maintain service over the greatest possible portion of the system under all conditions

(2) To disconnect only the line or apparatus in which a fault may develop

(3) To disconnect the faulty section from the remainder of the system in the shortest possible time in order to prevent trouble due to voltage drop over the healthy part of the system, which might cause the synchronous apparatus to drop out of step

(4) To prevent injurious heating due to short circuits or overloads

(5) To protect the apparatus from line surges and lightning discharges

In order to protect properly the apparatus, the following are the duties of the relays:

(1) Over-current protection of rotary converters, rotary condensers, frequency changers, motors, alternators, power transformers, etc.

TABLE III

Troubles of Transformers

Symptom	Trouble	Cause	Remedy
1. Temperature rises to the danger point on oil-cooled transformer	(a) Overload	(a) Overload or low power factor	(a) Reduce load or increase the power factor of the system. A 100-Kw. transformer at 80% power factor is fully loaded at 80 Kw.
	(b) Not sufficient oil in tank	(b) Due either to a leaky tank or not sufficient oil when installed	(b) Add more oil and weld tank. (NOTE: The core and coils should be fully immersed in oil.)
	(c) Oil jellied	(c) Excessive heat (NOTE: In a case of this kind the windings will be roasted and the insulation practically ruined.)	(c) If insulation is not damaged, flush the tank with new oil until all the old oil is removed, and then refill tank with fresh oil.
2. Temperature rises to the danger point on oil-cooled transformer	(a) Overload	(a) Overload or low power factor	(a) Reduce load or increase the power factor of the system. A 100-Kw. transformer at 80% power factor is fully loaded at 80 Kw.
	(b) Not enough volume of air	(b) Blower speed too low or air ducts clogged	(b) Speed up blower. Clean air ducts. (NOTE: In cleaning air ducts, care must be exercised. If compressed air is used, do not impress full voltage on windings immediately after, as there is always more or less moisture in compressed air. Voltage of not more than double the secondary or low voltage should be impressed on the high-voltage winding and the low-voltage winding short circuited. A transformer thus treated may be put back in service in about five hours.)
3. Temperature rises to the danger point on water-cooled transformer	(a) Overload	(a) Overload or low power factor	(a) Reduce load or increase the power factor of the system. A 100-Kw. transformer at 80% power factor is fully loaded at 80 Kw.
	(b) Not enough water flowing through cooling coils	(b) Pressure low or tubes obstructed	(b) Increase rate of water flow. If tubes are obstructed, clean with a solution of caustic soda and water.
	(c) Oil level below cooling coils	(c) Oil leakage around water inlet	(c) Stop leak and fill tank with fresh oil which should fully immerse cooling coils.

TABLE III —Continued

Troubles of Transformers

Symptom	Trouble	Cause	Remedy
	(d) No water flowing through cooling coils	(d) Cooling coils plugged	(d) Remove obstruction with water or air pressure up to 250 lbs. per sq. in. but no more, as coils are likely to be damaged. Where water contains lime or other impurities, the cooling coils should be cleaned at least every six months with a solution of equal parts of water and hydrochloric acid. This solution should be allowed to stand for not more than an hour and afterwards flushed out with clean water.
	(e) Oil saponified on outside of cooling coils	(e) Transformer operated at too low temperature	(e) If oil does not soften by overheating the cooling coils should be removed and scraped.
4. Temperature rises to the danger point on transformer and explosions occur in transformer tank	(a) Short circuit between adjacent layers of high voltage windings	(a) Moisture in oil or in air in case of air cooled transformer. Moisture in oil may be due to a leak in the cooling coil or to breathing. Breathing or sweating is caused from operating the transformer in a damp location at too low a temperature. Note: The temperature of a transformer should not fall below 10 degrees Centigrade.	(a) Test for moisture in oil. Measure the breakdown voltage required to force a spark through a gap between two brass balls immersed in the oil. Oil that is free from moisture should have a breakdown test of voltage of 25,000 volts when balls are 0.15 inch apart. Where this apparatus is not available the following test can be made: Heat a few crystals of copper sulphate (blue vitrol) on a hot plate until the crystals turn white. Take a small bottle and fill with oil from the bottom of the transformer tank, as this is where the moisture will collect, and drop a few grains of the heated vitrol in the oil. Shake well and if there is any moisture in the oil the solution will turn blue. If there is no moisture, it will remain a neutral color.*

*In getting a sample of oil the best method is to use a long glass tube. Close the end held in the hand by placing the thumb over the opening. When the tube is fully immersed remove the thumb and allow the tube to fill. Again place the thumb over the top opening and withdraw and the oil will remain in the tube.

If moisture is present pass the oil through a filter press which consists of a number of sections of filter or blotting paper. The usual filter consists of [illegible] sections of [illegible] x8" sheets or a total of [illegible]. The thickness of each section is about 0.[illegible]. The oil is forced at a pressure up to 250 lbs. per sq. in. and the time required for a large transformer is from four to five hours. The transformer need not be taken out of service while the oil is being filtered unless it is defective.

Before restoring the circuit of a defective transformer the transformer can be taken out of service and the service resumed on open delta if the transformer bank is delta connected. If star connected all transformers in the bank become inoperative. When operating two transformers on open delta the load should be reduced to 58 per cent of the load carried by the original bank.

TABLE III—Continued

Troubles of Transformers

Symptom	Trouble	Cause	Remedy
	(b) Short circuit between high- and low-voltage windings	(b) (1) Insulation broken down	(b) (1) Replace sections of winding causing the trouble.
		(2) Insulation punctured due to line surges	(2) Replace sections of winding causing trouble.
		(3) Shifting of coils due to switching on and off of heavy loads	(3) Replace sections of winding causing trouble.
		(4) Not enough insulation on the end turns. These should have from 2 to 5 times greater insulation than the inside turns	(4) Replace sections of winding causing trouble and reinsulate end turns to proper thickness.
		(5) Electro-magnetic stresses too great, due to improper core construction	(5) Transformer will need to be returned to factory to be rebuilt. This trouble will seldom be met with.
		(6) Transformer coils not properly baked before assembling	(6) Short circuit secondary and impress twice secondary voltage on primary windings.
		(7) Lightning discharge without protection	(7) Repair damaged coils or replace with new coils. (NOTE: All transformers should be protected by having choke coils or reactors in series with them.)
		(8) Oscillating currents, caused by conductors swinging together due to wind storms	(8) Replace sections of winding causing trouble.
		(9) Unstable voltage; generator voltage not steady	(9) Replace sections of winding causing trouble.
		(10) Insulation roasted by constant overhead	(10) Replace sections of winding causing trouble.

TABLE III—Continued

Troubles of Transformers

Symptom	Trouble	Cause	Remedy
	(c) Ground between low voltage winding and core	(c) (1) Lightning discharge	(c) (1) Repair damaged coils or replace with new coils.
		(2) Insulation breakdown due to line surge or shifting of coils	(2) Repair damaged coils or replace with new coils.
	(d) Short circuit on terminal board	(d) Moisture in oil	(d) Remove board, bake and re-varnish. Pass oil through a filter press.
	(e) Short circuit between high- or low-voltage bushings	(e) Bushings broken or cracked	(e) Replace bushings.
	(f) Improper division of load	(f) Parallel operation of transformers with different characteristics	(f) Transformers which are to be paralleled should have the same characteristics. If one bank has a high reactance and it is desired to parallel it with a bank having a low reactance, reactance coils must be inserted between the two banks.
	(g) Low-voltage windings punctured	(g) (1) Ground on high-voltage side of an ungrounded neutral delta-delta system	(g) (1) Remove ground, repair low-voltage windings, and ground both high- and low-voltage neutrals.
		(2) Ground on high-voltage side of a delta-delta system with the low-voltage neutral only, grounded	(2) Remove ground, repair low-voltage windings, and ground both high- and low-voltage neutrals.
5. Unequal heating in bank of star connected transformers with the neutral grounded	Ground on one phase	Defective insulation in transformer or ground on line, due to defective insulators, dead birds, kite strings, or other obstructions	Disconnect the bank from service immediately, since a trouble of this kind short circuits the bank. (NOTE: The insulation between the windings and core is limited to a voltage of 57.7% of the line voltage with a star connection; and if one phase or line is grounded, the voltage between the ground and the remaining two circuits is increased to as high as full line voltage in some cases.)

TABLE III—Continued

Troubles of Transformers

Symptom	Trouble	Cause	Remedy
6. Unequal heating in bank of transformers connected star primary, delta secondary	Ground on one of the primary phases	Defective insulation in transformer or ground on line, due to defective insulators, dead birds, kite strings, or other obstructions	Disconnect the bank until the trouble is removed as the bank cannot be operated on open delta, since if the secondary winding of the grounded transformer is short circuited, the voltage between the two outside lines will be increased by the line voltage times $\sqrt{3}$.
7. Voltage not the same in all phases of a three-phase bank of transformers	(a) Ground on one phase of a bank-connected star-delta. The voltage between two of the lines will be the voltage between the other two times $\sqrt{3}$.	(a) Broken insulator on line, line in contact with some obstruction leading to ground, defective insulation in transformer, bushing punctured, and terminal grounded	(a) Cut out the bank on which the defect occurs and remedy by removing cause of ground, replace insulators, bushings, or section of winding causing the trouble.
	(b) One transformer bucking the other two	(b) One transformer connected so that its polarity is opposite that of the others. If not cleared soon after noticed one or more of the transformers may burn out	(b) Change the polarity of the transformer causing the trouble. To test polarity, connect the primaries in parallel and the secondaries in parallel, with a fuse in series with the secondary windings. If transformers are of opposite polarity, the fuse will short circuit one transformer on the other and will consequently blow. If the fuse blows, interchange the leads and test until the fuse does not blow, when the polarities of all three will be the same.
8. Voltage too low	Wrong ratio	Leads not connected to proper ratio taps	Raise the taps to one higher, or until the voltage is correct.
9. Voltage too high	Wrong ratio	(a) Leads not connected to proper ratio taps	(a) Lower taps until voltage is correct.
		(b) Transformers paralleled that have different ratios	(b) Change ratios until all transformers are the same; or if this cannot be done, replace transformers.

(2) To prevent automatic opening of oil circuit breakers in case the current is above the interrupting capacity of the breaker

(3) Internal troubles of power transformers

(4) Internal troubles of alternators

(5) Single-phase operation or unbalanced load in three-phase alternators

(6) Unequal division of the load of alternators due to loads of prime mover

(7) Phase reversals

(8) Under-voltage protection of apparatus shown in No. (1)

In order to protect properly the feeders, the following are the duties of the relays:

(1) Over-current protection of lines

(2) To prevent the circuit breakers from automatically closing on the third operation. (NOTE: Automatically-controlled circuit breakers will try to close three times. If a short circuit or excessive load persists on the third attempt, the relay locks the breaker open and it cannot be closed until the line is cleared.)

(3) Under-current or open-circuit protection for circuits energized by constant-current transformers

(4) Over-power protection to disconnect lines in case the power exceeds a predetermined value

(5) Under-power protection to disconnect lines in case power falls below a predetermined value

(6) To protect against a fault in a single line

(7) To protect against faults in two parallel lines

(8) To protect against faults in three or more parallel lines

(9) To protect against reversal of normal power in the lines

NOTE: Reverse power relays are used in the last four instances.

Thus it can be readily seen that relays are the nervous system of a hydroelectric or any other system.

Testing relays

In order to determine whether a relay is functioning properly, it should be frequently tested. The various tests of relays include load, current, voltage, temperature, and timing.

All excess-current, under-current, and reverse-power relays depend on overload or underload for operation. An underload relay may be tested by simply reducing the load; but an overload relay cannot always be tested by overload, since the load is usually fixed and an overload only occurs when the circuit is short circuited.

Owing to the fact that when a circuit is in use, it is seldom desirable to interrupt it by imposing a short circuit and also, due to the effect of a short circuit on the switching equipment, it is unde-

sirable. In order to test a relay without interfering with the service, several methods are used, the most practical being given here.

The connections shown in Fig. 25 are for a load test using a separate load and trip circuit. The relay under test is disconnected from the trip circuit and current transformers and the transformer leads short circuited.

CAUTION: In connection with current transformers, care must be taken in opening the secondary circuit, as dangerous currents build up in them when open circuited. These currents are not only dangerous to the life of the operator but to the station equipment.

Near the secondary leads of a current transformer there will be found two bare wires, which are the ends of a piece of bare conductor

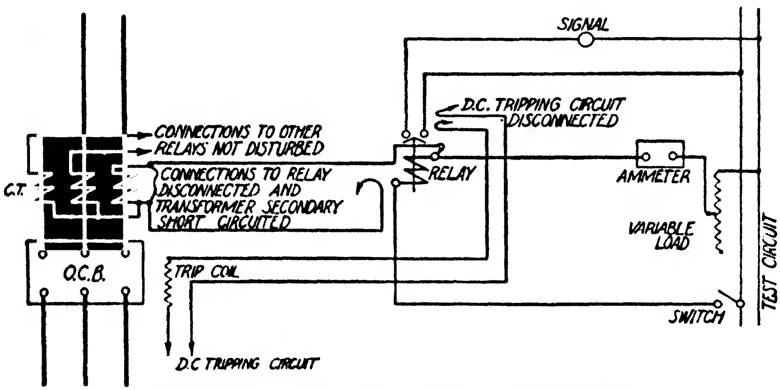


Fig. 25. Connections for Testing Relay from a Separate Circuit

embedded in the insulation. Before attempting to disconnect a current transformer, these ends should be firmly connected to the two secondary terminals, and under no consideration should they ever be removed while the secondary circuit through the relays and other instruments is open.

NOTE: When a new current transformer is received from the factory, never cut or remove these bare leads, since as long as they are in evidence it will give some indication of what they are used for.

Another method of testing, where the relay is not disconnected from the circuit, is shown in Fig. 26. In this test, the load is discontinued and the line must not be energized, in other words, it must be dead.

The load in each of the above tests may be supplied by a bank of lamps connected in parallel, the number being varied by simply removing one or more from their sockets; or by means of a carbon rheostat, a standard wire resistance, a water rheostat; or by a phantom load box. The resistance must be variable so as to vary the load.

In testing a relay, the time may be taken by a stop watch or by a cycle counter, the latter method being more reliable. The time is taken from the instant the load is switched on the relay until

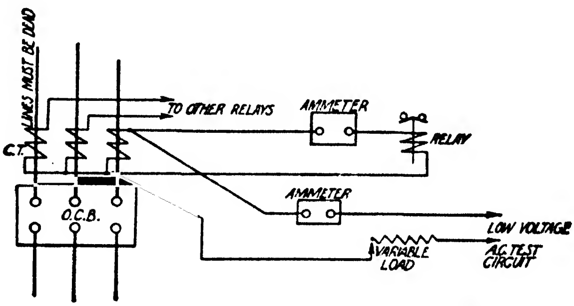


Fig. 26. Connections for Testing Relay without Disconnecting

the contacts of the trip circuit close or open as the case may be, and again when the relay resets itself or attains its normal position.

The cycle counter, the elements of which are shown in Fig. 27, consists of a self-winding clock similar to those used in Westinghouse graphic meters, in which the pendulum is replaced by a polarized relay. An indicating pointer is attached to the pendulum escapement wheel W and moves over a scale. The escapement bar at B allows the wheel to move one tooth at a time, as in an ordinary clock. Attached to the escapement bar is the armature, which is polarized by the magnets M and $M1$. The magnetic circuit is formed by the coils C and $C1$, which attract and repel the armature.

During the first half cycle the current is applied, the current flows in the coils at X and out at Y, and the right-hand end of the bar is repelled while the left-hand end is attracted. During the second half cycle, the current flows in at Y and out at X with the result that the left-hand end of the bar is repelled and the right-hand end attracted, and the wheel moves ahead another notch.

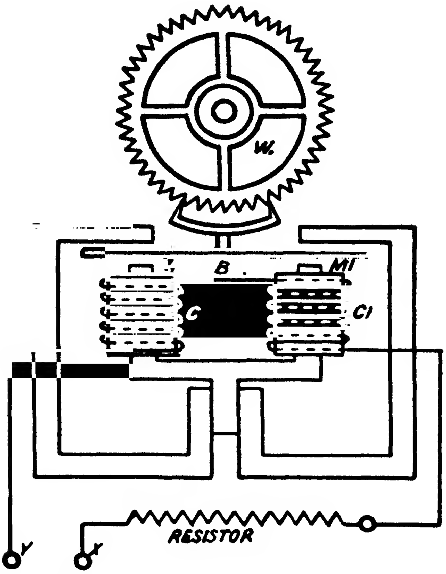


Fig. 27. Connections of a Cycle Counter

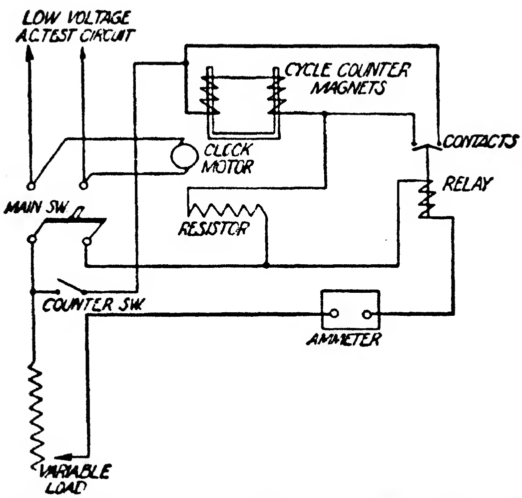


Fig. 28. Connections for Timing a Circuit-Closing Relay with a Cycle Counter

Fig. 28 shows the connections for timing a circuit-closing relay. The relay is disconnected from its circuit and connected to a low-voltage alternating-current test circuit. The load may be any of those mentioned previously and the circuit is provided with a switch for quickly putting the load on or off. The counter is also provided with a switch, as shown in the diagram. When all the switches are closed, the counter revolves until the relay contacts close, short circuiting the escapement magnets and stopping the counter. The time delay of the relay is then found by dividing the cycles indicated by the instrument by the number of cycles or normal frequency of

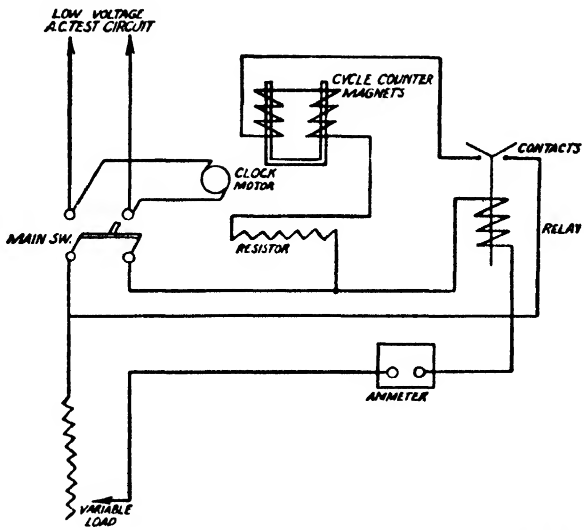


Fig. 29. Connections for Timing a Circuit-Opening Relay with a Cycle Counter

the circuit, i. e., if the frequency of the circuit is 60 cycles and the instrument indicates 90, the time delay or the time taken by the relay to trip the breaker under normal conditions is $90 \div 60$, or $1\frac{1}{2}$ seconds.

Fig. 29 shows the connections for timing a circuit-opening relay. In this connection, the same procedure is followed as in the circuit-closing relay, only the counter stops when the relay contacts open.

Fig. 30 shows the connections for testing a voltage relay from the existing circuit, while Fig. 31 shows the connections for testing

from a separate circuit. In these tests a potential transformer which may be used to either step up or step down the voltage is used, and

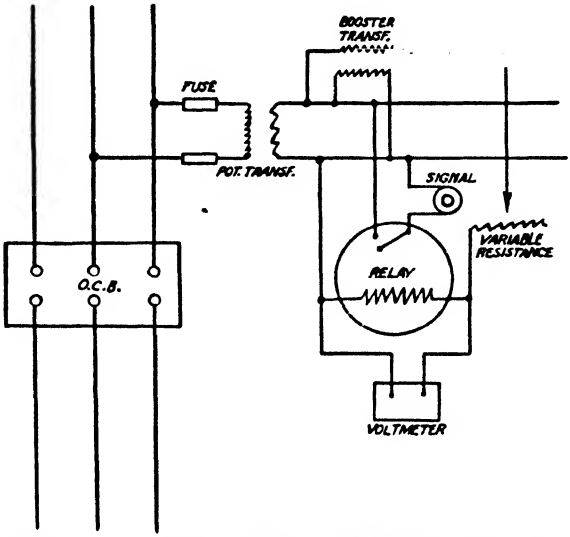


Fig. 30. Connections for Testing a Voltage Relay Direct from the Circuit

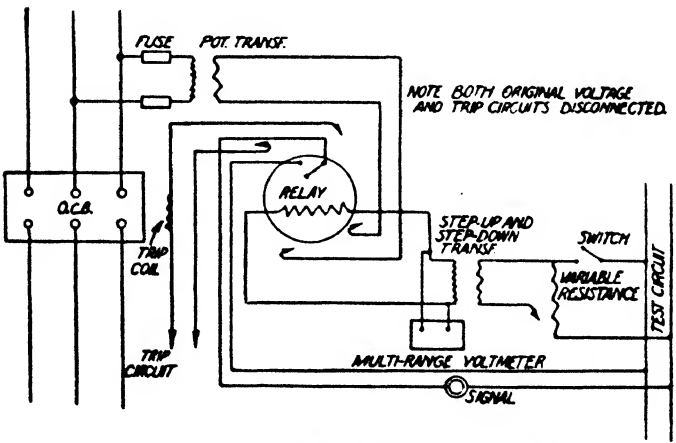


Fig. 31. Connections for Testing a Voltage Relay from a Separate Circuit

the variations of voltage between the standard ratio taps is provided for by means of an adjustable resistance in shunt with the line.

Adjusting relays

Generally speaking there are only two adjustments to be made—the current or overload adjustment and the adjustment to the timing element.

The current rating of the plunger type relays is adjusted by raising or lowering the plunger of the solenoids. This is done by turning the nut at the bottom of the plunger casing in the General Electric types, and by turning the plunger which is threaded on the stem in some of the other types.

The current rating of the induction type relays is adjusted by increasing or reducing the tension on the spiral spring which compensates or opposes the torque of the instrument. These relays which have a torque compensator may be adjusted by changing the position of the compensator in relationship to the base, which diverts the leakage flux and changes the current rating.

The time delay of the bellows type plunger relay is adjusted and changed by opening or closing the air-vent needle valve at the top of the instrument. The leather of the bellows should be kept pliable by the use of neat's-foot oil, as unpliable leather interferes with the functioning of the relay.

The time delay of the oil-lagged plunger type relay is adjusted by turning the dashpot piston so that the holes coincide in order that the oil may pass more freely when the time is to be shortened, and adjusted so that the holes close when the time is to be lengthened. Using a lighter or a heavier grade of oil also quickens and retards the time of this type.

The time delay of the induction type relay is adjusted by moving the magnets in respect to the disk. When the time is to be shortened, the magnet is moved toward the center of the disk, and when the time is to be lengthened, the magnet is moved toward the outer edge of the disk. In no case, however, should the magnets be moved greater than $\frac{1}{8}$ inch inside the outer edge of the disk.

Troubles of relays

Table IV covers the troubles usually encountered in relays, which as a general rule give very little trouble. So closely allied are relay troubles to those of oil circuit breakers that these troubles are also covered.

TABLE IV
Troubles of Relays

Symptom	Trouble	Cause	Remedy
1. Circuit breaker does not open when load reaches a point considerably in excess to normal relay setting	(a) Timing element defective	(a) Air vents closed too tightly	(a) Open air vents slightly. Oil the bellows with neat's-foot oil.
	(b) Plunger of plunger type relay jammed	(b) Heat from relay coil buckling the case in which the plunger moves, preventing it from moving	(b) Replace coil with a new one.
	(c) Disk of induction type relay rubbing or out of place	(c) Disk jewels broken or out of place, due to vibration	(c) Renew jewels.
	(d) Grease or dirt on relay contacts	(d) Relay cover not dust proof	(d) Remove all dust and grease.
2. Circuit breaker opens immediately on overload although a certain time delay was given the relay when last set and inspected	(a) Air escapes too freely from bellows of plunger type relay	(a) (1) Hole in bellows (2) Air vent open	(a) (1) Replace or patch bellows. (2) Close air vent.
	(b) Magnets out of adjustment in an induction relay	(b) Adjusting mechanism loose or broken by vibration	(b) Readjust position of magnets and tighten all screws.
3. Overload relay does not function although the relay itself is in perfect condition	(a) Contact circuit broken	(a) Accident or carelessness	(a) Repair.
	(b) Circuit between relay and current transformers open (NOTE: This will result in burning out the current transformers.)	(b) Accident or carelessness	(b) Repair.
	(c) Battery out of commission on D.C. trip or circuit closing relay	(c) Dry cells or storage battery not inspected, renewed or recharged often enough	(c) Renew dry cells. Recharge storage battery.

TABLE IV—Continued

Troubles of Relays

Symptom	Trouble	Cause	Remedy
	(d) Auxiliary or pallet switch does not open when breaker is closed	(d) Faulty switch mechanism	(d) Repair mechanical defect.
4. Circuit breakers will not stay closed where two or more are electrically interlocked	(a) Contacts on circuit closing auxiliary switch do not make contact	(a) Contacts bent or burned or contact toggle too tight	(a) Repair or replace contacts. Loosen and oil toggle.
	(b) Fuse on closing coil blown	(b) Short circuit in coil or circuit	(b) Install new coil and replace fuse.
	(c) Open circuit in closing coil or circuit	(c) Due to short circuit or mechanical defect	(c) Repair circuit or coil.
5. Circuit breakers will not open on overload where two or more are electrically interlocked	Contacts on circuit opening auxiliary switch do not make contact	Contacts bent or burned or contact toggle too tight	Repair or replace contacts. Loosen and oil toggle.
6. Circuit breakers open when underloaded, when provided with under-voltage coil, and none of the foregoing defects are apparent	Circuit to voltage coil open	Blown fuse or break in wiring	Repair break or replace fuse.

CARE AND MAINTENANCE OF LIGHTNING ARRESTERS

Lightning arresters used in the protection of hydroelectric equipment are either of the electrolytic or the oxide-film types. The first type requires a considerable amount of attention while the latter type requires only a periodical test.

Electrolytic arresters should be taken down at least every four years, since the electrolyte deteriorates with age and use. The following points should be thoroughly understood and precautions taken in either setting up a new arrester or reconditioning an old one.

Taking down and reconditioning lightning arrester

In taking down an electrolytic arrester, the arrester is disconnected from the line and the tanks stripped of all connections. The covers are next removed and the stacks lifted from the tanks and all oil and electrolyte poured from the cones. The top braces holding the brass conductor which are fastened to the posts are then removed and the cones lifted off one at a time. As soon as a cone is removed, it should be inverted and the insulating spacers placed upon it. The next cone is then removed and placed over the first but resting on the spacers. The remaining cones are treated in the same manner until all are removed. The cones and spacers are next washed in warm water mixed with castile soap or with plain naptha, the former being the better of the two. In handling the cones, handle by the rims only. As fast as the cones and spacers are washed and dried they are mounted in the stack again, but before mounting they should be examined for pits and burned spots. Never scrape a cone. When the stack is complete, it should be immediately filled with electrolyte which should be received fresh from the factory. The electrolyte is placed in the cones by means of a filler, Fig. 32, supplied by the factory.

The glass cone filler *A* is filled with electrolyte and the tube from the container allowed to fill by holding it below the level of *A*. When filled, the pinch cock *D* is closed and the tubing inserted in the container. This allows the electrolyte to be siphoned from the container. The glass tube *B* should be at a height in *A* for the proper amount of liquid for each cone section, depending on the distance between cones, as shown in the diagram. Close pinch cock *C* and open *D* until the liquid is the proper height and then close *D*. Insert

the tube between the stacks, starting at the bottom and open C. When A is empty, move the tube E to the next cone and repeat the operation until all the cones are filled. As each cone is filled, it should be checked. A spring clip clothes pin answers this purpose.

If a cell is filled twice, the excess should be siphoned out. This as well as a non-filled cone will be readily determined when the cells

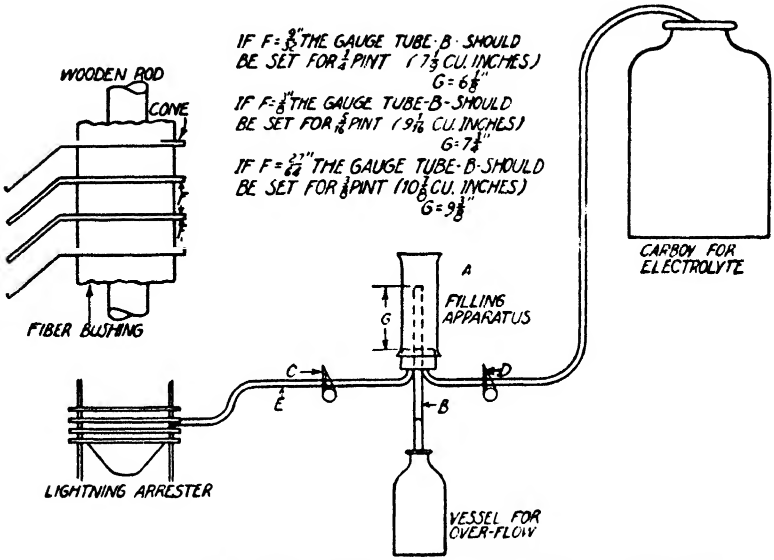


Fig. 32. Apparatus Used and Method of Filling Cone Stacks of Aluminum Cell Arresters

receive their preliminary charge, as illustrated in Fig. 33. Care should be used that no electrolyte is allowed on the insulating separators between the cones, nor on the wooden rods supporting the cones.

Testing an electrolytic arrester

As soon as the cells of one stack are filled, each cell must be tested as shown in Fig. 33, to see that the films are properly formed and that no cell has been missed or filled twice. A sufficient number of lamps are connected to limit the current to 2 amperes when the cell is not in circuit.

Starting at the bottom cell, a test plug is inserted between two cones of a cell. When contact is made, there should be a spark shown. If no spark is shown, the cell is empty, which will also be indicated

by no reading of the ammeter. When the cell is filming properly, the voltage should increase to practically full voltage across the cell and the current decrease from 2 amperes to .2 or .4 amperes, depending on the frequency of the circuit. The cell should be left on circuit about 10 seconds, depending on whether the cell is new or has been

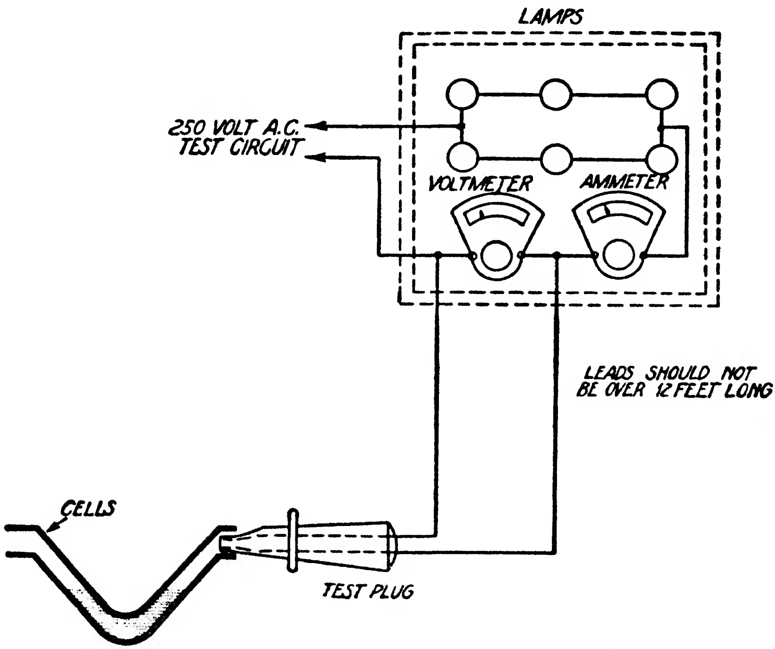


Fig. 33. Connections for Testing Aluminum Cell Arresters

previously charged. In no case should contact be made long enough to heat the electrolyte.

A double-filled cell will be indicated by taking approximately twice as much current as a properly filled cell. Each cell should be marked as in filling so that none may be missed. After completing the test of each cell, the whole stack should be tested by connecting one lead of the test circuit to the top cone and the other lead to the bottom cone. If no current indication or spark is shown, there is an empty cell in the stack.

If a voltmeter and ammeter are not available, the lamps may be used to indicate the condition of the film. When the plug is inserted

between the cones, the lamps should at first burn at full brilliance and after 10 seconds testing should dim. If the lamps do not burn brightly at first, it indicates that the film is formed; and if they do not light, it indicates an empty cell. There is no way of telling if a cell has been filled twice by this method.

500, 250, or 125 volts alternating current may be used for testing. The above data is for 250-volt tests. If the test voltage is 500 volts, two cells must be tested in series each time. If only 125 volts is available, charging or film forming is not accomplished, and only an indication of whether the cells are filled is had.

If direct current only is available, the cones should be charged twice with the connections reversed each time; and when finished, the whole stack should be discharged to ground before it is handled on account of the high voltage which might be built up in the stack.

As fast as the stacks are tested and charged, they should be put into the tanks and the tanks filled with oil. The oil should be filtered and either pumped in at the bottom of the tank or filled from the top. If it is filled from the top, it should be run in a tube to the bottom, so that it will not splash and force the electrolyte from the cells. The oil level should be such as to allow for expansion. The oil supplied usually has a coefficient of expansion of 0.0008 inches per lineal inch per degree centigrade. For arresters up to and including 50,000 volts, the oil level should be three inches from the top of the tanks. Above 50,000 volts, the level should be four inches from the top.

Operation of electrolytic arresters

As soon as the arrester is completely assembled, it should be immediately put into service and charged in order to keep the cone films in proper condition. The charging should be done six or eight times a day for the first day and three times a day for the remainder of the first week. After the first week, once a day is sufficient when the room or outside temperature is not excessive. In stations or outdoors when the temperature is excessive, the arrester should be charged twice daily.

When charging the arrester, the time for each charge should be between 5 and 10 seconds and never greater, and the arc should be quickly extinguished, as a prolonged arc will heat up the electrolyte

and dissolve the film. If possible, the first charge should be at reduced voltage. Practically the only way by which the voltage can be reduced with the average installation is by lowering the voltage of the alternators and gradually bringing the voltage up to normal. When charging the arrester, the condition of the film can be detected by the arc across the horns. If the arc is white and flaring and rises halfway or more to the top of the horns, it indicates excessive current. Usually this is the case with the first charge. As the film forms, the arc becomes less flaring and does not rise so high on the horns.

When the film is perfect and the arrester is in perfect operating condition, the arc should be reddish yellow in daylight and should extinguish before it reaches half the height of the horns. When the arrester has been charged, the horns are locked in their normal position, and care must be taken that they are not moved far enough to start an arc. To be sure of this, the operator must have a clear view of the gaps. If for any reason the horns are left short circuited, the oil and electrolyte will heat up and ruin the cells.

Maintenance of electrolytic arresters

The cones should be inspected at least once a year and during a time when electrical storms do not occur. When inspecting, the arrester should be disconnected and the cells lifted from the tanks. The excess oil should be siphoned off and the cells tested. If the cones show a normal condition, the stacks may be put back in service and the arrester charged.

If some of the cells do not form film, these should be marked and the electrolyte removed. If the oil is carbonized or the cones pitted, it shows that the electrolyte has been excessively hot and probably boiled down. It might be necessary to remove these cones, but since those at the top of the stack will be the ones usually affected, the work of overhauling is not great. If the cones are not pitted, they should be washed and dried, filled with new electrolyte, tested and charged, and put immediately into service.

If, however, several of the cones throughout the stack show signs of abnormal conditions, it is necessary to take down the entire stack. When rebuilding the stack if any of the old cones are used, they should be mounted in the bottom of the stack and any new ones

should be mounted at the top. It is not a good practice to use old and new cones in the same stack unless only a very few new ones are required. It is much better to take down two stacks and build one entirely of the best of the old cones and the other stack of all new cones.

Arresters should be periodically inspected for loose connections and broken or chipped insulators. They should be kept free from dust and oil. All iron work should be painted and the copper conductors and connections shellaced. The transfer mechanism should operate perfectly and the gap settings should be inspected and adjusted if out of adjustment. The ground connections are probably the most important items to watch and should be tested at regular intervals. A good ground element should not exceed 5 ohms.

Testing an oxide film arrester

Oxide film arresters are tested for deterioration with a vacuum tube testing device. The device consists of a calibrated gap in a glass vacuum tube or bulb mounted on a long stick of well-seasoned wood, with contacts which can be placed against the metal plates of the cell.

The arrester when being tested is short circuited on the line, which causes a drop across the cells in proportion to their resistance. A cell of high resistance will have a large drop and will cause the bulb to glow. The cell then can be easily removed and a new one inserted. The above test is for arresters on voltages above 7500 volts, as no satisfactory method has been found for testing those on lower voltages.

Troubles of lightning arresters

Very seldom is trouble encountered with oxide film arresters. If they are hit by a direct lightning stroke, they are usually ruptured completely and will need replacing; but as a direct stroke seldom reaches the arresters (nearly all discharges are induced), they seldom give any trouble.

Electrolytic arresters on the other hand often develop trouble, although not always of a serious nature. The usual troubles encountered are given in Table V, but if the arresters are given the right amount of attention, the trouble they will cause will be slight.

TABLE V

Troubles of Electrolytic Lightning Arresters

Symptom	Trouble	Cause	Remedy
1. Gaps continue to arc when set in operating position	Abnormal arcing	(a) Too small gap setting	(a) Increase gap setting.
		(b) Gap electrodes out of shape	(b) Straighten horns to proper alignment.
		(c) Voltage greater than normal due to crossing with higher voltage lines	(c) Repair lines if crossed.
		(d) Generator voltage too high	(d) Adjust generator voltage.
		(e) Films not properly formed	(e) Examine cells and renew defective ones.
2. Arc at horns or sphere gap too intense	Excessive charging current	(a) Improper charging	(a) Use proper method of charging in regard to time, holding the gaps on short circuit not longer than 5 to 10 seconds.
		(b) Arcing ground on line at time of charging	(b) Locate and repair causes of ground or abnormal arcing.
		(c) Electrolyte deteriorated	(c) Renew electrolyte in cells.
3. A rumbling noise issues from tanks	Arcing in oil	(a) One or more empty cells	(a) Fill cells with electrolyte.
		(b) One or more punctured cones	(b) Remove and replace with new cones, putting new cones at top of stack.
		(c) Electrolyte in contact with wooden rods or insulating spacers	(c) Wash all traces of electrolyte from rods and spacers and see that same does not come in contact when refilling and assembling.
4. Oil is thrown from tanks	Arcing in oil	(a) One or more empty cells	(a) Fill cells with electrolyte.
		(b) One or more punctured cones	(b) Remove and replace with new cones, putting new cones at top of stack.
		(c) Electrolyte in contact with wooden rods or insulating spacers	(c) Wash all traces of electrolyte from rods and spacers and see that same does not come in contact when refilling and assembling.

TABLE V—Continued

Troubles of Electrolytic Lightning Arresters

Symptom	Trouble	Cause	Remedy
		(d) Electrolyte becomes heated due to prolonged short circuit of horns or sphere gaps	(d) When this happens, the electrolyte becomes boiled down and it is usually necessary to take down the entire stack, clean each cone, renew any cones which may be punctured, or of which the film is gone, and refill and charge the arrester.*
5. A sizzling or crackling noise issues from the tanks	Due to scintillation	Voltage concentration on any spots on the cell not properly filmed	This does no real harm unless it is aggravated and becomes the same as symptom (4). Unless this happens, no notice need be taken of this symptom.
6. A sizzling or crackling noise issues from some part of the arrester outside the tanks	Leakage current	(a) Dust or moisture on insulators and resistance units	(a) Clean insulators, frame work, and resistance units; and remove all traces of moisture.
		(b) Cracked or chipped insulators	(b) Renew defective insulators.
7. Arcing at points of arrester mechanism other than the horns	(a) Loose or broken connections	(a) Carelessness in assembling or due to prolonged arcs due to short circuiting of horns	(a) Repair loose connection and polish all contacts with sandpaper and shellac all current-carrying parts.
	(b) Broken ground connection	(b) Corrosion or damage	(b) Repair break, first cutting the arrester from the line. The arrester is useless and also a hazard when the ground connection is broken, and therefore all ground connections should be periodically inspected and tested. One ground should never be depended upon, two or three being necessary.

*In taking down the stacks of aluminum cell arresters, each cone should be lifted from the wooden supports separately, handling them by the rim only. The content is emptied out and the cell washed with gasoline or ivory soap and water (the latter being preferred) and thoroughly dried with fine cheese cloth. As each cell or cone is finished, it is inverted with insulating spacers, which should also be washed and dried, between them. In this manner the cones will occupy the same position when again assembled. The cells when assembled should be immediately filled with electrolyte to the height called for by the manufacturer, charged, and immediately put into service.

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